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CHEMICAL AND PHYSICAL PROPERTIES OF ASPHALT- RUBBER MIXTURES — PHASE III

VOLUME 1

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16. Abstract

This study had the objectives of (1) evaluating the effects of major components, rubber and asphalt, on physical properties of asphalt-rubber mixtures, and (2) evaluating the feasibility of using testing procedures studied for specifying asphalt-rubber mixtures.

Forty-eight different asphalt-rubber mixtures formulated with six different rubber types at four concentrations with two asphalts were tested. Testing procedures utilized included absolute viscosity at 140F, Schweyer Rheometer and force-ductility at 39.2F, sliding plate microviscometer at 32.0F, and viscosity by the Torque-Fork and Haake viscometer during mixing at 375F. All mixtures were produced in a Torque-Fork mixer at 375F using a 1 hour mixing duration. A total of 31 measured or calculated parameters are reported and discussed.

The study concluded that physical properties of asphalt-rubber mixtures can vary widely depending on rubber type, rubber concentration, asphalt grade, and interactions between component materials.

The force-ductility and sliding plate microviscometer tests yielded several parameters with testing variability low enough to permit use in specifying asphalt-rubber physical properties.

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1.0 EXPERIMENT DESCRIPTION

1.1 This experiment had the following objectives:

A. To evaluate the effects of major components, rubber and asphalt, and related concentrations of these components on several physical properties of asphalt-rubber mixtures.

B. To evaluate the feasibility of using the testing procedures employed in this investigation for asphalt-rubber specification purposes.

1.2 A high degree of success was realized for objective A.

Success was realized for objective B in that several parameters obtained from the force-ductility and sliding plate microviscometer tests have low enough testing variability to permit use in specifying asphalt-rubber materials properties.

1.3 The laboratory investigation was conducted to determine the effects of constituent materials, rubber and asphalt, on physical properties of asphalt-rubber mixtures. Six different rubber types at four concentrations, and two asphalt types were studied.

1.3.1 Granulated rubber utilized was produced from two different reclamation processes and materials:

- Ambient grind tread peel crumb (Atlos)
- Ambient grind high natural rubber content devulcanized crumb (U.S. Rubber Reclaiming)

1.3.2 Three different gradations (particle size distributions) from each rubber production process were used making the total of six different rubber types as follows:

- TPO44
- TPO27
- 50/50 mix (by weight) of TPO27 and TPO27
- GT274
- USRF
- 50/50 mix (by weight) of GT274 and USRF

1.3.3 Each rubber type was incorporated into asphalt rubber mixtures at four concentration levels - 15, 20, 25, and 30 percent by weight of total mixture.

1.3.4 The two asphalts used in the study were Sahuaro AR1000 and Arco AR4000 from sources commonly used in commercial production of asphalt-rubber mixtures. Two percent of an extender oil was used in AR4000 mixtures. Details on materials properties of asphalts and rubbers studied are contained in the project Summary Report (1).

1.3.5 Asphalt-rubber mixtures were all prepared for testing using a standard mixing procedure in the Arizona Torque Fork as described in the project Summary Report (1).

1.4 Materials properties assessed in this study are:

- Absolute viscosity at 140F (60C)
- Apparent viscosity and shear rate sensitivity by the Schweyer Rheometer at 39.2F (4C)
- Stress, strain, and creep compliance properties at 39.2F (4C) using Force-Ductility
- Apparent viscosity, creep, strain recovery, rebound and rheological characteristics at 32.0F (0C) using the Sliding Plate Microviscometer
- Viscosity during mixing at 375F (191C) using the Arizona Torque Fork
- Viscosity during mixing at 375F (191C) using the Haake Rotational Viscometer.

1.4.1 Using the testing procedures described above, a total of 31 different parameters were evaluated, analyzed and reported. Testing details and calculations are contained in the project Summary Report (1).

2.0 EXPERIMENTAL DESIGN AND DATA ANALYSIS

2.1 The experiment was designed as a sequentially randomized, three factor fixed factorial model with two replications per cell. The experimental matrix is presented in Figure 1. The first randomization was by rubber type. Within rubber type, rubber concentration, asphalt cement, and replication were randomized.

2.1.1 The fixed factor model is:

$$Y_{ijkl} = \mu + R_i + Q_j + A_k + (RQ)_{ij} + (RA)_{ik} + (QA)_{jk} + (RQA)_{ijk} + \varepsilon_{(ijk)l}$$

where:

Y_{ijkl} = Response variable (viscosity, Schweyer constants, etc.) for the i^{th} level of rubber type, j^{th} level of rubber concentration, k^{th} level of asphalt type and l^{th} replication.

μ = Effect of overall mean.

R_i = Effect of rubber type.

Q_j = Effect of rubber concentration.

A_k = Effect of asphalt type.

$(RQ)_{ij}$, $(RA)_{ik}$, $(QA)_{jk}$ = Second order interactions.

$(RQA)_{ijk}$ = Third order interaction.

$\varepsilon_{(ijk)l}$ = Experimental error.

2.1.2 Degrees of freedom for the analysis are as follows:

Source	Degrees of Freedom
R_i	5
Q_j	3
A_k	1
$(RQ)_{ij}$	15
$(RA)_{ik}$	5
$(QA)_{jk}$	3
$(RQA)_{ijk}$	15
Error	48
Total	95

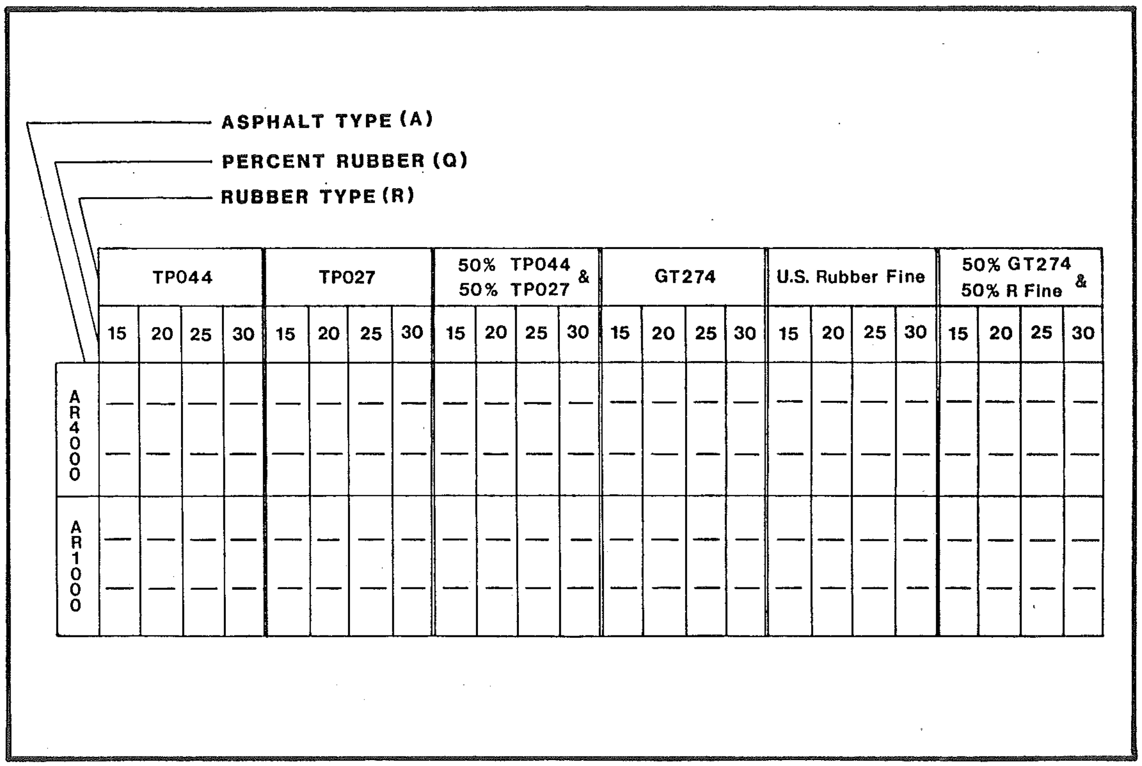

Figure 1 Experimental Test Matrix

2.1.3 Data were analyzed using conventional three-way analysis of variance techniques.

2.1.4 Prior to analysis, homogeneity of variance was tested by the Foster and Burr q-test (2). Appropriate data transformations were used when necessary to comply with variance homogeneity constraints required for analysis of variance. It should be pointed out that due to the nature of tests and variability of some asphalt-rubber formulations, extensive use was made transformed data.

2.2 Levels of Independent Variables

2.2.1 Rubber at six levels as follows:

- TP044
- TP027
- 50/50 mix (by weight) of TP027 and TP044
- GT274
- USRF
- 50/50 mix (by weight) of GT274 and USRF

2.2.2 Rubber quantities at four levels, 15, 20, 25, and 30 percent, by weight of the asphalt-rubber mixture.

2.2.3 Asphalt at two levels - AR4000 and AR1000.

2.3 Analysis of Simple Main Effects.

2.3.1 Following completion of the three-way ANOVA, with many of the experimental parameters, two-way ANOVA on simple main effects were performed to aid in data interpretation. Analyses were performed for each rubber type, concentration, and asphalt grade.

2.3.1.1 The analysis model for each rubber type is:

$$Y_{ijk} = \mu + A_i + Q_j + (AQ)_{ij} + \varepsilon_{(ij)k}$$

in which:

Y_{ijk} = Response variable for the i^{th} level of asphalt, the j^{th} level of rubber concentration, and k^{th} replication

μ = Effect of overall mean

A_i = Effect of asphalt type

Q_j = Effect of rubber concentration

$(AQ)_{ij}$ = Effect of asphalt-concentration interaction

$(ij)k$ = Experimental error

Degrees of freedom for this analysis model are:

Source	Degrees of Freedom
A_i	1
Q_j	3
$(AQ)_{ij}$	3
Error	8
Total	15

2.3.1.2 The analysis model for each rubber concentration is:

$$Y_{ijk} = \mu + A_i + R_j + (AR)_{ij} + \varepsilon_{(ij)k}$$

in which:

Y_{ijk} = Response variable for the i^{th} level of asphalt, the j^{th} level of rubber type, and the k^{th} replication.

μ = Effect of overall mean

A_i = Effect of asphalt type

R_j = Effect of rubber type

$(AR)_{ij}$ = Effect of asphalt-rubber type interaction

$\varepsilon_{(ij)k}$ = Experimental error

Degrees of freedom for this analysis model are:

Source	Degrees of Freedom
A_i	1
R_j	5
$(AR)_{ij}$	5
Error	12
Total	23

2.3.1.3 The analysis model for each asphalt grade is:

$$Y_{ijk} = \mu + R_i + Q_j + (RQ)_{ij} + \varepsilon_{(ij)k}$$

in which:

Y_{ijk} = Response variable for the i^{th} level of rubber type, the j^{th} level of rubber concentration, and the k^{th} replication.

μ = Effect of overall mean

R_i = Effect of rubber type

Q_j = Effect of rubber concentration

$(RQ)_{ij}$ = Effect of rubber-concentration interaction

$\varepsilon_{(ij)k}$ = Experimental error

Degrees of freedom for this analysis model are:

Source	Degrees of Freedom
R_i	5
Q_j	3
$(RQ)_{ij}$	15
Error	24
Total	47

3.0 RESULTS AND DISCUSSIONS

3.1 Absolute Viscosity

3.1.1 Measured vacuum capillary absolute viscosity results at 140F (60C) are tabulated in Appendix A in Table A-1. Each value tabulated in Table A-1 is the average of viscosity values obtained from several bulbs of one viscometer. Two viscosity tests were performed for each matrix cell replication.

3.1.1.1 Average coefficient of variation for Atlos rubber at all concentrations and both asphalts was 33.9 percent compared to 22.3 percent for the U.S. Rubber Reclaiming rubber.

3.1.1.2 Average coefficients of variation for each rubber type at all concentrations and for both asphalts are:

- TP044 - 63.4%
- TP027 - 13.5%
- 50/50 TP044/TP027 - 24.8%
- GT274 - 31.7% (16.8% if one measurement not considered)
- USRF - 18.6%
- 50/50 GT274/USRF - 16.6%

3.1.1.3 Average coefficients of variation for each rubber concentration for all rubber types and both asphalts are:

- 15% - 26.0%
- 20% - 26.0%
- 25% - 27.7%
- 30% - 32.8%

3.1.1.4 Average coefficients of variation for all mixtures containing AR4000 asphalt was 25.3 percent, and for the AR1000, 25.8 percent.

3.1.1.5 In several cases (TP044, AR1000, with 20 and 25 percent rubber; and 50/50 GT274/USRF, AR1000, with 25 percent rubber) large differences are noted between mean replicate values, but within replicates, variability was low. This may be due to segregation of the mixture during sampling, or in other words, separation by drainage of asphalt. It is interesting to note that these differences are noted only with the AR1000 asphalt, and not the AR4000 which would be less prone to drain or separate due to its higher viscosity.

3.1.1.6 Variability of measured absolute viscosity as indicated by coefficient of variation appears to be:

- greater for larger rubber particles than fine,
- greater for higher rubber concentrations than low, and
- not affected by asphalt grade.

3.1.2 The data which were statistically analyzed are tabulated in Appendix A in Table A-2. Each value tabulated in Table A-2 is the mean of the two measured values in Table A-1. Analyzed data are plotted in Appendix A in Figures A1 through A13.

3.1.3 During data analysis, several attempts were made to transform the data to comply with variance homogeneity requirements, but success was not realized due to the high variability of the TP044 data. Therefore, the data analysis were split and two separate ANOVA performed - one for the full factorial without TP044 and one for the TP044 data only. Transformations were not required to satisfy variance homogeneity requirements. These ANOVA summaries are tabulated in Tables A-3 and A-4.

3.1.3.1 For the analysis without TP044, rubber type, concentration, rubber-concentration interaction, rubber-asphalt interaction, and the rubber-concentration-asphalt interaction are significant effects at the 0.01 level. Asphalt is significant at the 0.05 level but not the 0.01, and the concentration-asphalt interaction is not significant at the 0.05 level.

3.1.3.2 For the analysis with only TP044, concentration is a significant effect at the 0.05 level but not the 0.01 level. Asphalt and asphalt-concentration interaction are not significant at the 0.05 level.

3.1.4 Analyses of results show that rubber type, rubber concentration, asphalt, and several interactions influence the measured absolute viscosity of asphalt-rubber mixtures at 140F(60C).

3.1.4.1 Effect of Rubber Type. Asphalt-rubber mixtures containing USRF rubber had the highest absolute viscosity (225,7000 poise overall average) while mixtures containing TPO44 and GT274 rubber had the lowest (122,800 poise and 122,600 poise respectively). Mixtures containing Atlos rubber had approximately the same average absolute viscosity values (122,800 poise, TPO44; 127,900 poise, TPO27; and 129,100 poise, 50/50 TPO44/TPO27).

For mixtures containing U.S. Rubber Reclaiming rubber, the smaller particle size, USRF rubber, resulted in a higher average absolute viscosity than the larger, GT274 (225,700 poise, USRF; 122,600 poise, GT274).

3.1.4.2 Effect of Rubber Concentration. Examination of Figures A4 through A9 shows that for all asphalt-rubber mixtures tested, as rubber concentration increases, absolute viscosity increases (20,600 poise overall average at 15 percent rubber compared to 374,600 poise at 30 percent). Two-way ANOVA by rubber type shows that concentration is a significant effect for all rubber types. Two-way ANOVA by asphalt type shows that concentration is also significant for both AR1000 and AR4000. Two-way ANOVA by concentration shows that at 15 and 20 percent, differences in absolute viscosity of mixtures exist due to asphalt and rubber type. However, at 25 percent, differences exist only due to rubber type, and at 30 percent, differences are not noted due to asphalt or rubber type.

3.1.4.3 Effect of Asphalt. Two-way ANOVA by rubber type shows that asphalt is a significant effect for mixtures containing TPO27, GT274, and USRF but not for TPO44, 50/50 TPO44/TPO27, or 50/50 GT274/USRF. Two-way ANOVA by rubber concentration shows that asphalt is significant at 15 and 20 percent, but not at 25 or 30 percent rubber. These trends can be seen in Figures A4 through A9.

Absolute viscosity of asphalt-rubber mixtures containing AR4000 is slightly higher than that of mixtures containing AR1000 for all rubber types except USRF at 25 and 30 percent rubber. With these two mixtures, higher absolute viscosities were measured with the AR1000 asphalt as can be seen in Figure A8. These higher viscosities may be due to a greater degree of rubber and asphalt reaction resulting from the high surface area of the rubber and the thinner asphalt which could result in increased swelling of rubber particles.

3.2 Schweyer Rheometer Constant, G-tube

3.2.1 Measured rheometer constants using the G-tube are tabulated in Appendix B in Table B-1.

3.2.1.1 Average coefficient of variation for Atlos rubber at all concentrations and both asphalts was 25.2 percent compared to 24.3 percent for the U.S. Rubber Reclaiming rubber.

3.2.1.2 Average coefficients of variation for each rubber type at all concentrations and for both asphalts are:

- TP044 - 31.9%
- TP027 - 23.6%
- 50/50 TP044/TP027 - 20.2%
- GT274 - 19.2%
- USRF - 19.0%
- 50/50 GT274/USRF - 34.1%

3.2.1.3 Average coefficients of variation for each rubber concentration for all rubber types and both asphalts are:

- 15% - 23.4%
- 20% - 28.3%
- 25% - 25.8%
- 30% - 21.5%

3.2.1.4 Average coefficient of variation for all mixtures containing AR4000 asphalt was 23.1 percent, and for the AR1000, 26.5 percent.

3.2.1.5 Variability of measured rheometer constant G-tube data as indicated by coefficient of variation does not appear to be influenced by rubber particle size (although there is a possible increase in variability with TP044), rubber concentration, or asphalt grade.

3.2.2 The measured data did not require transformations to provide for variance homogeneity prior to analysis. Analyzed data are plotted in Appendix B, Figures B1 through B12.

3.2.3 The ANOVA summary for rheometer constant G-tube data is tabulated in Table B-2.

3.2.3.1 Rubber type was a significant effect at the 0.01 level. Concentration was significant at the 0.05 level but not at the 0.01 level. Asphalt and all interactions were not significant effects at the 0.05 level.

3.2.4 Analyses of results show that the type of rubber and rubber concentration influence rheometer constant C (shear susceptibility) measured with the G-tube of asphalt-rubber mixtures at 39.2F(4C).

3.2.4.1 <u>Effect of Rubber Type</u>. Asphalt-rubber mixtures containing the 50/50 TPO44/TPO27 rubber mixture had the highest shear susceptibility constant in the G-tube, (0.76 overall average) while the USRF mixture had the lowest (0.46 overall average).

Mean shear susceptibility constant for mixtures containing Atlos rubber was 0.74 and for mixtures containing U.S. Rubber Reclaiming rubber, 0.50. Therefore, it appears that asphalt-rubber mixtures which contain U.S. Rubber Reclaiming rubber are more pseudoplastic in behavior than are mixtures which contain Atlos rubber.

3.2.4.2 Effect of Rubber Concentration. Average overall shear susceptibility constant at 15 percent rubber is 0.70 and at 30 percent rubber, 0.55. Examination of Figures B3 through B8 shows that the mean shear susceptibility constant slightly decreases as rubber concentration increases for each rubber type. Therefore, it appears that as rubber concentration increases, the asphalt-rubber mixtures become more pseudoplastic in behavior.

3.2.4.3 Effect of Asphalt. Asphalt grade was found not to have an effect on the shear susceptibility constant of asphalt-rubber mixtures tested in the G-tube.

3.2.4.4 With the exception of two mixtures (TP044, AR1000 with 15 and 25 percent rubber) all mixtures had shear susceptiblity constants which were less than 1.0 as shown in Figure B2 indicating that the asphalt-rubber mixtures tested were pseudoplastic (viscosity decreases as shear rate increases). Average shear susceptibility constant measured using the G-tube was 0.62.

3.3 Schweyer Rheometer Constant, F-tube

3.3.1 Measured rheometer constants using the F-tube are tabulated in Appendix C in Table C-1 and plotted in Figures C1 through C12.

3.3.1.1 Average coefficient of variation for Atlos rubber at all concentrations and both asphalts was 26.7 percent compared to 30.3 percent for the U.S. Rubber Reclaiming rubber.

3.3.1.2 Average coefficients of variation for each rubber type at all concentrations and for both asphalts are:

- TP044 - 35.4%
- TP027 - 15.5%
- 50/50 TP044/TP027 - 29.3%
- GT274 - 30.1%
- USRF - 24.1%
- 50/50 GT274/USRF - 36.8%

3.3.1.3 Average coefficients of variation for each rubber concentration for all rubber types and both asphalts are:

- 15% - 26.8%
- 20% - 37.5%
- 25% - 24.5%
- 30% - 25.3%

3.3.1.4 Average coefficient of variation for all mixtures containing AR4000 asphalt was 35.7 percent, and for the AR1000, 21.4 percent.

3.3.1.5 Variability of measured rheometer constant F-tube data as indicated by coefficient of variation appears to be:

- greater for larger rubber particle sizes,
- greatest at a 20% rubber concentration,
- greater for AR4000 than for AR1000 asphalt cement

3.3.2 In order to satisfy variance homogeneity requirements, arctangent transformations of data were required prior to analysis. Arctangent transformed data are tabulated in Appendix C in Table C-2 and plotted in Figures C13 through C24.

3.3.3 The ANOVA summary for rheometer constant, F-tube, is tabulated in Table C-3.

3.3.3.1 Rubber type, concentration, rubber-concentration interaction and, rubber-asphalt interaction were significant at the 0.01 level. The rubber-concentration-asphalt interaction was significant at the 0.05 level, but not at 0.01. Asphalt and the concentration-asphalt interaction were not significant at the 0.05 level.

3.3.4 Analyses of results show that rubber type, rubber concentration, and several interactions influence rheometer constant C (shear susceptibility) measured with the F-tube of asphalt-rubber mixtures at 39.2F(4C).

3.3.4.1 Effect of Rubber Type. Asphalt-rubber mixtures containing TPO27 and the 50/50 TPO44/TPO27 mixture had the highest shear susceptibility constant in the F-tube (1.10 overall average for TPO27 and 1.09 for the 50/50 TPO44/TPO27 mixture) while the USRF mixtures had the lowest (0.82 overall average).

Mixtures containing Atlos rubber had higher shear susceptibility constants in the F-tube than mixtures containing U.S. Rubber Reclaiming rubber (1.01 overall average for Atlos compared to 0.87 overall average for U.S. Rubber Reclaiming).

As indicated by the measured shear susceptibility constant using the F-tube, asphalt-rubber materials containing Atlos rubber tend to be slightly dilatent in shear susceptibility behavior while mixtures containing U.S. Rubber Reclaiming rubber are slightly pseudoplastic.

3.3.4.2 Effect of Rubber Concentation. Examination of Figures C3 through C8 shows that rubber concentration appears to slightly influence shear susceptibility constant values in the F-tube mixtures containing Atlos Rubber, (1.30 average at 15 percent rubber compared to 0.94 at 30 percent rubber).

Data indicate that as rubber concentration increases, asphalt-rubber materials tend to become slightly more pseudoplastic in behavior.

3.3.4.3 Effect of Asphalt. Asphalt grade was found to not have an effect on shear susceptibility constant of asphalt-rubber mixtures tested in the F-tube.

3.3.4.4 It is interesting to note that differences exist in measured shear susceptibility constant values depending on rheometer tube size used (refer to sections 3.2.4.1 and 3.2.4.2). With the smaller tube size (F), shear susceptibility values are greater than with the larger tube (G). Considering the increased particle interference to flow in the smaller rheometer tube, asphalt-rubber mixtures would be expected to be more dilatent in behavior with smaller tubes than with larger tubes. This trend is indicated in the data.

3.4 Schweyer Rheometer Apparent Viscosity ($\eta_{0.05}$) at 39.2F (4C), G-tube

3.4.1 Measured apparent viscosity data using the G-tube are tabulated in Appendix D in Table D-1 and plotted in Figures D1 through D12.

3.4.1.1 Average coefficient of variation for Atlos rubber at all concentrations and both asphalts was 86.8 percent compared to 48.9 percent for the U.S. Rubber Reclaiming rubber.

3.4.1.2 Average coefficients of variation for each rubber type at all concentrations and for both asphalts are:

- TP044 - 78.4%
- TP027 - 97.0%
- 50/50 TP044/TP027 - 67.3%
- GT274 - 41.1%
- USRF - 31.6%
- 50/50 GT274/USRF - 73.7%

3.4.1.3 Average coefficients of variation for each rubber concentration for all rubber types and both asphalts are:

- 15% - 74.2%
- 20% - 76.1%
- 25% - 65.8%
- 30% - 55.4%

3.4.1.4 Average coefficient of variation for all mixtures containing AR4000 asphalt was 71.3 percent, and for the AR1000, 64.4 percent.

3.4.1.5 Variability of measured apparent viscosity G-tube data as indicated by coefficient of variation appears to be:

- greater for Atlos rubber than for U.S. Rubber Reclaiming rubber possibly due to larger particle sizes of Atlos rubber,
- greater for lower rubber concentrations, and
- not affected by asphalt type.

3.4.2 In order to satisfy variance homogeneity requirements, logarithmic transformations of the data were required prior to analysis. Log transformed data are tabulated in Appendix D in Table D-2 and plotted in Figures D13 through D24.

3.4.3 The ANOVA summary for apparent viscosity, G-tube is tabulated in Table D-3.

3.4.3.1 Rubber type was a significant effect at the 0.01 level. Asphalt was significant at the 0.05 level but not at 0.01. Rubber concentration and all interactions were not significant at the 0.05 level.

3.4.4 Analyses of results show that the type of rubber and asphalt influence measured apparent viscosity at a 0.05 sec^{-1} shear rate of asphalt-rubber mixtures at 39.2F(4C) using the G-tube.

3.4.4.1 <u>Effect of Rubber Type</u>. Asphalt-rubber mixtures containing the 50/50 TPO44/TPO27 mixture had the highest average apparent viscosity in the G-tube (231 x 10^6 Pa-s overall average) while mixtures containing USRF rubber had the lowest (33 x 10^6 Pa-s overall average).

Mixtures containing Atlos rubber had higher viscosities than mixtures containing U.S. Rubber Reclaiming rubber (184 x 10^6 Pa-s overall average for Atlos compared to 41 x 10^6 Pa-s for U.S. Rubber Reclaiming).

3.4.4.2 <u>Effect of Rubber Concentration</u>. Rubber concentration was not found to influence apparent viscosity in the G-tube. This can be noted in Figures D3 through D8.

3.4.4.3 Effects of Asphalt. Examination of Figures D3 through D12 shows that mixtures containing AR4000 asphalt generally have slightly higher apparent viscosity in the G-tube than mixtures containing AR1000 (181 Pa-s overall average for AR4000 compared to 12.6 Pa-s for AR1000).

3.4.5 It is noted that for many of the asphalt-rubber mixtures tested reporting the mixture viscosity at a 0.05 sec^{-1} shear rate required extrapolation of the data in several cases by as much as 2 orders of magnitude which could be a contributing factor to the high degree of variability of apparent viscosity test results. More extrapolation was required with Atlos than with U.S. Rubber Reclaiming mixtures. Reporting viscosity at a shear rate closer to the measured data may decrease variability of results.

3.5 Schweyer Rheometer Apparent Viscosity ($\eta_{0.05}$) at 39.2F (4C), F-tube

3.5.1 Measured apparent viscosity data using the F-tube are tabulated in Appendix E in Table E-1 and plotted in Figures E1 through E12.

3.5.1.1 Average coefficient of variation for Atlos rubber at all concentrations and both asphalts was 59.1 percent compared to 60.4 percent for the U.S. Rubber Reclaiming rubber.

3.5.1.2 Average coefficients of variation for each rubber type at all concentrations and for both asphalts are:

- TP044 - 70.3%
- TP027 - 39.5%
- 50/50 TP044/TP027 - 67.5%
- GT274 - 59.9%
- USRF - 56.0%
- 50/50 GT274/USRF - 53.7%

3.5.1.3 Average coefficients of variation for each rubber concentration for all rubber types and both asphalts are:

- 15% - 65.2%
- 20% - 68.0%
- 25% - 71.5%
- 30% - 34.3%

3.5.1.4 Average coefficient of variation for all mixtures containing AR4000 asphalt was 73.8 percent, and for the AR1000, 45.8 percent.

3.5.1.5 Variability of measured apparent viscosity F-tube data as indicated by coefficient of variation appears to be:

- greater for larger rubber particles,
- least at high rubber concentrations, and
- less for AR1000 than for AR4000 asphalt cement

3.5.2 In order to satisfy variance homogeneity requirements, log log transformations of the data were required prior to analysis. Log log transformed data are tabulated in Appendix E in Table E-2 and plotted in Figures E13 through E24.

3.5.3 The ANOVA summary for apparent viscosity, F-tube is tabulated in Table E-3.

3.5.3.1 Rubber type, concentration, asphalt, rubber-concentration interaction, and rubber-asphalt interactions were significant effects at the 0.01 level. Other interactions were not significant at the 0.05 level.

3.5.4 Analyses of results show that rubber type, rubber concentration, asphalt, and several interactions influence the measured apparent viscosity at a 0.05 sec^{-1} shear rate of asphalt-rubber mixtures at 39.2F(4C) using the F-tube.

3.5.4.1 Effect of Rubber Type. Asphalt-rubber mixtures containing the 50/50 GT274/USRF mixture had the highest average apparent viscosity in the F-tube (1583 x 10^6 Pa-s overall average) and the USRF mixtures, the lowest (654 x 10^6 Pa-s overall average). It should be noted that averaged data are misleading due to high variability and presence of several extreme values.

3.5.4.2 <u>Effect of Rubber Concentration</u>. Average data show that for Atlos rubber mixtures containing 15 percent rubber, average apparent viscosity is 1027 x 10^6 Pa-s compared to 1618 x 10^6 Pa-s at 30 percent rubber in the F-tube. For mixtures containing U.S. Rubber Reclaiming rubber, average apparent viscosity is 11,675 x 10^6 Pa-s at 15 percent rubber and 85 x 10^6 Pa-s for 30 percent rubber. These data indicate that for Atlos mixtures, as concentration increases, apparent viscosity increases, and that for U.S. Rubber Reclaiming mixtures, as concentration increases, viscosity decreases. It is noted, though, that presence of several extreme values and resulting high variability of data may cause these observations to be misleading.

3.5.4.3 <u>Effect of Asphalt</u>. Overall average apparent viscosity in the F-tube for AR4000 mixtures was 2113 x 10^6 Pa-s compared to 655 x 10^6 Pa-s for AR1000 mixtures which tends to indicate that AR4000 mixtures have a higher apparent viscosity in the F-tube than AR1000 mixtures. Once again, this observation may be misleading due to high variability.

3.5.4.4 It is interesting to note that the measured apparent viscosity of asphalt-rubber mixtures in the F-tube are higher than in the G-tube (section 3.4.4.1). Additionally, testing variability as indicated by coefficient of variation is greater in the F-tube. It is believed that the smaller capillary diameter of the F-tube (4.65 mm compared to 9.700 mm for the G-tube) is the cause of these differences due to increased flow interference from the rubber particles.

3.5.5 Again, as with apparent viscosity measured with the G-tube, extrapolation of data was required to report viscosity at a 0.05 sec^{-1} shear rate with many of the mixtures which may be causing the high degree of testing variability.

3.6 Force-Ductility Load at Failure at 39.2F (4C)

3.6.1 Measured force ductility load at failure data are tabulated in Appendix F in Table F-1. Three measurements were obtained for each matrix cell replicate.

3.6.1.1 Average coefficient of variation for Atlos rubber at all concentrations and both asphalts was 9.2 percent compared to 7.6 percent for the U.S. Rubber Reclaiming rubber.

3.6.1.2 Average coefficients of variation for each rubber type at all concentrations and for both asphalts are:

- TP044 - 10.1%
- TP027 - 11.3%
- 50/50 TP044/TP027 - 6.2%
- GT274 - 5.5%
- USRF - 6.2%
- 50/50 GT274/USRF - 11.0%

3.6.1.3 Average coefficients of variation for each rubber concentration for all rubber types and both asphalts are:

- 15% - 8.9%
- 20% - 7.8%
- 25% - 8.8%
- 30% - 8.0%

3.6.1.4 Average coefficient of variation for all mixtures containing AR4000 asphalt was 8.5 percent, and for the AR1000, 8.3 percent.

3.6.1.5 Variability of measured force ductility load at failure data as indicated by coefficient of variation does not appear to be effected by rubber particle size, rubber concentration, or asphalt grade.

3.6.2 Analyzed load at failure data are tabulated in Table F-2 and plotted in Figures F1 through F12. Each entry in Table F-2 is the mean of three measurements from Table F-1.

3.6.3 The ANOVA summary for force ductility load at failure is tabulated in Table F-3.

3.6.3.1 All main effects and two-way interactions are significant at the 0.01 level, and the rubber-concentration-asphalt interaction is significant at the 0.05 level but not at the 0.01.

3.6.4 Analyses of results show that rubber type, rubber concentration, asphalt, and several interactions influence load at failure in the force-ductility test at 39.2F(4C).

3.6.4.1 Effect of Rubber Type. Asphalt-rubber mixtures containing the 50/50 TPO44/TPO27 rubber had the highest load at failure (24.6 pound overall average) while mixtures containing GT274 rubber had the lowest (13.8 pound overall average).

Mixtures containing Atlos rubber failed at higher loads (18.6 pound overall average) than mixtures containing U.S. Rubber Reclaiming rubber (14.6 pound overall average).

It is interesting to note that for Atlos rubber, the 50/50 mixture of TPO44 and TPO27 rubbers resulted in higher loads at failure than either of the two individual rubbers. This trend was not noted with the 50/50 GT274/USRF rubber mixture.

3.6.4.2 Effect of Rubber Concentration. Examination of Figures F3, F4, and F5 shows that for Atlos rubber mixtures, as rubber concentration increases, load at failure increases (13.3 pound average at 15 percent rubber compared to 25.1 pound average at 30 percent). Two-way ANOVA by rubber type shows that for each of the Atlos rubbers, concentration is a significant effect.

Examination of Figures F6, F7, and F8 shows that rubber concentration does not greatly influence load at failure of U.S. Rubber Reclaiming mixutres to the extent as with Atlos rubber.

Average loads at failure for U.S. Rubber Reclaiming mixtures tend to increase slightly as rubber concentration increases, reach a maximum at 20 to 25 percent rubber, and then drop slightly at 30 percent rubber (overall average loads at failure of 13.2 pounds at 15 percent rubber, 16.2 pounds at 20 percent, 15.2 pounds at 25 percent, and 14.4 pounds at 30 percent). Two-way ANOVA by rubber type shows that concentration is a significant effect for GT274 mixtures, but not for USRF or the 50/50 GT274/USRF mixtures.

3.6.4.3 Effect of Asphalt. Examination of Figures F3 through F12 shows that with only one exception, mean load at failure values are higher for asphalt-rubber mixtures containing the AR4000 asphalt than the AR1000 asphalt (19.9 pound overall average for AR4000 compared to 13.2 pounds for AR1000).

As rubber concentration increases, differences between loads at failure of AR4000 and AR1000 mixtures are observed to decrease indicating that at high rubber concentration loads at failure are influenced to a lesser extent by asphalt characteristics than at low rubber concentrations.

3.7 Force-Ductility Elongation at Failure at 39.2F (4C)

3.7.1 Measured force ductility elongation at failure data are tabulated in Appendix G in Table G-1. Three measurements were obtained for each matrix cell replicate.

3.7.1.1 Average coefficient of variation for Atlos rubber at all concentrations and both asphalts was 8.1 percent compared to 8.9 percent for the U.S. Rubber Reclaiming rubber.

3.7.1.2 Average coefficients of variation for each rubber type at all concentrations and for both asphalts are:

- TP044 - 9.0%
- TP027 - 7.5%
- 50/50 TP044/TP027 - 7.8%
- GT274 - 6.0%
- USRF - 8.6%
- 50/50 GT274/USRF - 12.6%

3.7.1.3 Average coefficient of variation for each rubber concentration for all rubber types and both asphalts are:

- 15% - 8.8%
- 20% - 7.5%
- 25% - 8.4%
- 30% - 9.2%

3.7.1.4 Average coefficients of variation for all mixtures containing AR4000 asphalt was 8.1 percent, and for the AR1000, 9.1 percent.

3.7.1.5 Variability of measured elongation at failure data as indicated by coefficient of variation does not appear to be affected by rubber particle size, rubber concentration, or asphalt grade.

3.7.2 Reduced elongation at failure data are tabulated in Table G-2 and plotted in Figures G1 through G12. Each entry in Table G-2 is the mean of three values from Table G-1.

3.7.3 In order to satisfy variance homogeneity requirements, logarithmic transformations of data were required prior to analysis. Log transformed data are tabulated in Appendix G in Table G-3 and plotted in Figures G13 through G24.

3.7.4 The ANOVA summary for elongation at failure is tabulated in Table G-4.

3.7.4.1 Rubber type, concentration, asphalt, rubber-concentration interaction and concentration-asphalt interaction are significant effects at the 0.01 level. The rubber-concentration-asphalt interaction is significant at the 0.05 level but not at 0.01. The rubber-asphalt interaction is not significant at the 0.05 level.

3.7.5 Analyses of results show that rubber type, rubber concentration, asphalt, and several interactions influence elongation at failure test results at 39.2F(4C).

3.7.5.1 Effect of Rubber Type. Asphalt-rubber mixtures containing GT274 rubber had the highest elongation at failure (413 mm overall average) while TPO44 mixtures had the lowest (207 mm overall average).

Atlos rubber mixtures had lower elongations at failure (268 mm average) than U.S. Rubber Reclaiming mixtures (378 mm average).

For Atlos mixtures, data indicates that rubber composed of small particles (TPO27) results in larger elongations at failure than rubbers with larger particles (TPO44). This trend is not noted with U.S. Rubber Reclaiming rubbers as mixtures containing GT274 (larger particles) had higher elongations at failure than those containing USRF (smaller particles).

3.7.5.2 Effect of Rubber Concentration. Examination of Figures G3, G4, and G5 shows that for Atlos rubber mixtures as rubber concentration increases, elongation at failure decreases (316 mm average at 15 percent rubber compared to 239 mm average at 30 percent). Two-way ANOVA by rubber type for each Atlos rubber indicates that concentration is a significant effect.

Two-way ANOVA by rubber type for each of the U.S. Rubber Reclaiming rubbers indicate that concentration is significant with GT274 and the 50/50 GT274/USRF mixture, but, is not with USRF. These trends can be seen in Figures G6, G7, and G8.

3.7.5.3 Effect of Asphalt. Except for four of the asphalt-rubber mixtures investigated, mixtures containing AR1000 asphalt cement failed at higher elongation values than mixtures containing AR4000 (347 mm overall average for AR1000 compared to 299 mm for AR4000). Examination of Figures G3 through G12 shows that as rubber concentrations increase, differences in elongation at failure between mixtures containing AR4000 and AR1000 tend to decrease indicating that at high rubber concentrations, elongations at failure are influenced to a lesser extent by asphalt characteristics than at low rubber concentrations.

3.8 Force-Ductility Engineering Stress at Failure at 39.2F (4C)

3.8.1 Engineering stress at failure data are tabulated in Appendix H in Table H-1. Three determinations were obtained for each matrix cell replication.

3.8.1.1 Average coefficient of variation for Atlos rubber at all concentrations and both asphalts was 9.3 percent compared to 7.6 percent for the U.S. Rubber Reclaiming rubber.

3.8.1.2 Average coefficients of variation for each rubber type at all concentrations and for both asphalts are:

- TP044 - 10.1%
- TP027 - 11.4%
- 50/50 TP044/TP027 - 6.2%
- GT274 - 5.5%
- USRF - 6.2%
- 50/50 GT274/USRF - 10.9%

3.8.1.3 Average coefficients of variation for each rubber concentration for all rubber types and both asphalts are:

- 15% - 9.0%
- 20% - 7.9%
- 25% - 8.8%
- 30% - 8.0%

3.8.1.4 Average coefficient of variation for all mixtures containing AR4000 asphalt was 8.5 percent, and for the AR1000, 8.3 percent.

3.8.1.5 Variability of measured engineering stress at failure data as indicated by coefficient of variation does not appear to be influenced by rubber particle size, rubber concentration, or asphalt grade

3.8.2 Analyzed engineering stress at failure data are tabulated in Appendix H in Table H-2 and plotted in Figures H1 through H12. Each entry in Table H-2 is the mean of three values from Table H-1.

3.8.3 The ANOVA summary for engineering stress at failure is tabulated in Table H-3.

3.8.3.1 Rubber, concentration, asphalt, rubber-concentration interaction, rubber-asphalt interaction, and concentration-asphalt interaction are significant effects at the 0.01 level. The rubber-concentration-asphalt interaction was not significant at the 0.05 level.

3.8.4 Analyses indicate that rubber type, rubber concentration, asphalt, and several interactions influence engineering stress at failure of asphalt-rubber mixtures during the forceductility test.

3.8.4.1 Effect of Rubber Type. Asphalt-rubber mixtures containing the 50-50 TP044/TP027 mixture had the highest average engineering stress at failure values (153.7 psi overall average) while the GT274 mixtures had the lowest (85.9 psi overall average).

Data indicate that mixtures containing Atlos rubber had higher engineering stress at failure values (121.6 psi overall average) than mixtures containing U.S. Rubber Reclaiming rubber (91.3 psi overall average).

Additionally, it is noted that the mixture of TP044 and TP027 rubber resulted in higher engineering stress at failure values than either of the individual rubbers alone.

3.8.4.2 Effect of Rubber Concentration. Examination of Figures H3, H4, and H5 shows that for asphalt-rubber mixtures containing Atlos rubber, as rubber concentration increases, engineering stress at failure increases. Engineering stress at failure for asphalt-rubber mixtures which contain U.S. Rubber Reclaiming rubber, on the other hand, is not influenced by rubber concentration to the extent as mixtures containing Atlos rubber as shown in Figures H6, H7, and H8. Two-way ANOVA by rubber type indicates that rubber concentration is a significant effect at the 0.01 level for all rubber types except USRF and the 50-50 GT274/USRF mixture.

3.8.4.3 Effect of Asphalt. Examination of Figures H3 through H8 shows that mixtures containing AR4000 asphalt have higher engineering stress at failure than mixtures containing AR1000 asphalt. This may be due to the greater viscosity and stiffness of the AR4000 as compared to the AR1000. Overall average engineering stress at failure for mixtures containing AR4000 is 129.3 psi compared to 83.6 psi for mixtures containing AR1000 asphalt.

3.9 Force-Ductility Engineering Strain at Failure at 39.2F (4C)

3.9.1 Engineering strain at failure values are tabulated in Appendix I in Table I-1. Three determinations were obtained for each matrix cell replication.

3.9.1.1 Average coefficient of variation for Atlos rubber at all concentrations and both asphalts was 7.4 percent compared to 7.8 percent for the U.S. Rubber Reclaiming rubber.

3.9.1.2 Average coefficients of variation for each rubber type at all concentrations and for both asphalts are:

- TP044 - 8.3%
- TP027 - 8.0%
- 50/50 TP044/TP027 - 5.8%
- GT274 - 4.5%
- USRF - 6.6%
- 50/50 GT274/USRF - 12.2%

3.9.1.3 Average coefficients of variation for each rubber concentration for all rubber types and both asphalts are:

- 15% - 7.5%
- 20% - 6.3%
- 25% - 8.2%
- 30% - 8.2%

3.9.1.4 Average coefficient of variation for all mixtures containing AR4000 asphalt was 6.9 percent, and for the AR1000, 8.2 percent.

3.9.1.5 Variability of measured engineering strain at failure data as indicated by coefficient of variation does not appear to be affected by rubber particle size, concentration, or asphalt grade.

3.9.2 Reduced engineering strain at failure data are tabulated in Appendix I in Table I-2 and plotted in Figures I1 through I12. Each entry in Table I-2 is the mean of three values from Table I-1.

3.9.3 In order to satisfy variance homogeniety requirements, log transformations of the data were required prior to analysis. Log transformed data are tabulated in Appendix I in Table I-3 and plotted in Figures I13 through I24.

3.9.4 The ANOVA summary for engineering strain at failure is tabulated in Table I-4.

3.9.4.1 Rubber, concentration, asphalt, rubber-concentration interaction, and concentration-asphalt interaction are significant effects at the 0.01 level. Rubber-concentration-asphalt interaction is significant at the 0.05 level but not at the 0.01. Rubber-asphalt interaction is not significant at the 0.05 level.

3.9.5 Analyses indicate that rubber type, rubber concentration, asphalt, and several interactions influence engineering strain at failure of asphalt-rubber mixtures during the force-ductility test.

3.9.5.1 <u>Effect of Rubber Type</u>. Asphalt-rubber mixtures containing GT274 rubber had the highest engineering strain at failure (8.12 mm/mm overall average) and mixtures containing TP044 rubber, the lowest (3.92 mm/mm overall average).

Data indicates that for asphalt-rubber mixtures containing Atlos rubber, as particle size increases, for all rubber concentrations, engineering strain at failure decreases (see Figures I9 through I12). For mixtures containing U.S. Rubber Reclaiming rubber, GT274 rubber, the largest rubber of this type investigated, resulted in highest average engineering strain at failure results (8.12 mm/mm).

Mixtures containing Atlos rubber failed at lower average engineering strains (5.2 mm/mm average) than those contaning U.S. Rubber Reclaiming rubber (7.4 mm/mm average).

3.9.5.2 Effect of Rubber Concentration. Examination of Figures I3 through I8 shows that as rubber concentration increases, engineering strain at failure decreases for all rubber types except USRF. Two-way ANOVA performed by rubber type indicate that rubber concentration is a significant effect for all rubber types except USRF. Overall average engineering strain at failure for mixtures containing 15 percent rubber was 6.6 mm/mm and for 30 percent rubber, 5.5 mm/mm.

3.9.5.3 Effect of Asphalt. Examination of Figures I3 through I12 shows that generally, at 15 and 20 percent rubber concentrations, mixtures containing AR1000 asphalt failed at higher engineering strains than mixtures containing AR4000 asphalt.

At 25 and 30 percent rubber concentrations, there are less differences in failure strains between AR1000 and AR4000 mixtures than at 15 and 20 percent rubber. Two-way ANOVA by rubber concentration shows that asphalt is a significant effect at 15 and 20 percent rubber, but not at 25 and 30 percent rubber.

3.10 Force-Ductility True Stress at Failure at 39.2F (4C)

3.10.1 Force-ductility true stress at failure data are tabulated in Appendix J in Table J-1. Three determinations were obtained for each matrix cell replication.

3.10.1.1 Average coefficient of variation for Atlos rubber at all concentrations and both asphalts was 11.8 percent compared to 10.9 percent for the U.S. Rubber Reclaiming rubber.

3.10.1.2 Average coefficients of variation for each rubber type at all concentrations and for both asphalts are:

- TP044 - 13.7%
- TP027 - 13.4%
- 50/50 TP044/TP027 - 8.3%
- GT274 - 9.1%
- USRF - 9.2%
- 50/50 GT274/USRF - 14.3%

3.10.1.3 Average coefficients of variation for each rubber concentration for all rubber types and both asphalts are:

- 15% - 9.8%
- 20% - 9.6%
- 25% - 12.3%
- 30% - 13.6%

3.10.1.4 Average coefficient of variation for all mixtures containing AR4000 asphalt was 11.8 percent, and for the AR1000, 10.8 percent.

3.10.1.5 Variability of measured true stress at failure data as indicated by coefficient of variation does not appear to be influenced by rubber particle size or asphalt grade. Increasing rubber concentrations may slightly increase variability.

3.10.2 Analyzed true stress at failure data are tabulated in Appendix J in Table J-2 and plotted in Figures J1 through J12.

3.10.3 The ANOVA summary for true stress at failure data is tabulated in Table J-3.

3.10.3.1 Rubber, concentration, asphalt, rubber-concentration interaction and concentration-asphalt interaction are significant effects at the 0.01 level. Rubber-asphalt and rubber-concentration-asphalt interactions are not significant at the 0.05 level.

3.10.4 Analyses indicate that rubber type, rubber concentration, asphalt, and several interactions influence true stress at failure of asphalt-rubber mixtures during the force-ductility test.

3.10.4.1 Effect of Rubber Type. Asphalt-rubber mixtures containing the 50/50 TPO44/TPO27 rubber had the highest true stress at failure (878 psi overall average) while mixtures containing TPO44 rubber had the lowest (532 psi overall average). For mixtures containing Atlos rubber, the smaller particle size (TPO27) resulted in higher true stress at failure than the TPO44 (730 psi compared to 532 psi). The mixture of TPO44 and TPO27 resulted in higher true stress at failure than either TPO44 or TPO27.

Mixtures containing U.S. Rubber Reclaiming rubber failed at approximately the same average true stress values, 767 psi for GT274, 786 psi for USRF, and 700 psi for the GT274/USRF mixture.

3.10.4.2 Effect of Rubber Concentration. Examination of Figures J3, J4, and J5 shows that for asphalt-rubber mixtures containing Atlos rubber, as concentration increases, true stress at failure tends to increase (545 psi at 15 percent rubber compared to 860 psi at 30 percent). Two-way ANOVA by rubber type shows that for each of the Atlos rubbers, concentration is a significant effect.

Figure J6 shows that for mixtures containing GT274, as concentration increases, true stress at failure increases, but then drops when rubber concentration exceeds 25 percent. Two-way ANOVA on GT274 mixtures indicate that concentration is a significant effect.

Two-way ANOVA on USRF and GT274/USRF mixtures, on the other hand shows that concentration is not a significant effect. This can be noted in Figures J7 and J8.

Two-way ANOVA performed by asphalt indicates that concentration is a significant effect for asphalt-rubber containing AR1000, but not for mixtures containing AR4000.

3.10.4.3 Effect of Asphalt. Examination of Figures J3 through J12 shows that true stress at failure for mixtures containing AR4000 asphalt is higher than for mixtures containing AR1000 asphalt (854 psi overall average for AR4000 compared to 610 psi for AR1000). Two-way ANOVA by rubber type shows that asphalt is a significant effect. The same is noted when ANOVA is performed by rubber concentration.

3.11 Force-Ductility True Strain at Failure at 39.2F (4C)

3.11.1 True strain at failure data are tabulated in Appendix K in Table K-1. Three determinations were obtained for each matrix cell replication.

3.11.1.1 Average coefficients of variation for Atlos rubber at all concentrations and both asphalts was 3.4 percent compared to 3.3 percent for the U.S. Rubber Reclaiming rubber.

3.11.1.2 Average coefficients of variation for each rubber type at all concentrations and for both asphalts are:

- TP044 - 4.2%
- TP027 - 3.3%
- 50/50 TP044/TP027 - 2.7%
- GT274 - 2.0%
- USRF - 2.8%
- 50/50 GT274/USRF - 5.0%

3.11.1.3 Average coefficients of variation for each rubber concentration for all rubber types and both asphalts are:

- 15% - 3.3%
- 20% - 2.7%
- 25% - 3.6%
- 30% - 3.8%

3.11.1.4 Average coefficient of variation for all mixtures containing AR4000 asphalt was 3.1 percent, and for the AR1000, 3.6 percent.

3.11.1.5 Variability of measured true strain at failure data as indicated by coefficient of variation is low (less than 5 percent based on averages) and does not appear to be effected by rubber particle size, concentration, or asphalt grade.

3.11.2 Analyzed true strain at failure data are tabulated in Appendix K in Table K-2 and plotted in Figures K1 through K12.

3.11.3 The ANOVA summary for true strain at failure is tabulated in Table K-3.

3.11.3.1 Rubber, concentration, asphalt, rubber-concentration interaction, and concentration-asphalt interaction are significant effects at the 0.01 level. The rubber-concentration-asphalt interaction is significant at the 0.05 level but not at 0.01. The rubber-asphalt interaction is not significant at the 0.05 level.

3.11.4 Analyses indicate that rubber type, rubber concentration, asphalt, and several interactions influence true strain at failure of asphalt-rubber mixtures during the force-ductility test.

3.11.4.1 Effect of Rubber Type. Asphalt-rubber mixtures containing GT274 rubber failed at highest true strains (2.20 mm/mm overall average) and mixtures containing TP044, the lowest (1.59 mm/mm overall average). For mixtures containing Atlos rubber at all concentrations, the smaller rubber particle size (TP027) resulted in higher true strain at failure than for TP044, the largest rubber particle size (2.03 mm/mm compared to 1.59 mm/mm). This trend can be seen in Figures K9 through K12.

For mixtures containing U.S. Rubber Reclaiming rubber, smaller differences in average results were noted than for the Atlos rubber mixtures (2.20 mm/mm overall average for GT274, 2.06 mm/mm for USRF, and 2.07 mm/mm for 50-50 GT274/USRF).

3.11.4.2 <u>Effect of Rubber Concentration</u>. Examination of Figures K3 through K8 shows that for all rubber types except USRF, as concentration increases, true strain at failure tends to slightly decrease (2.08 mm/mm overall average for 15 percent rubber compared to 1.87 mm/mm for 30 percent rubber). Two-way ANOVA by rubber type indicates that concentration is a significant effect for all rubbers except USRF.

3.11.4.3 <u>Effect of Asphalt</u>. Examination of Figures K3 through K12 shows that generally, true strains at failure for mixtures containing AR4000 asphalt are less than for AR1000 asphalt (1.90 mm/mm overall average for the AR4000 compared to 2.01 mm/mm for AR1000 mixutres).

Additionally, it is noted that as rubber concentration increases, true strains at failure obtained for AR4000 and AR1000 mixtures tend to become closer for all rubber types indicating that at higher rubber concentrations, asphalt characteristics have a lesser effect on true strain at failure than at lower rubber concentrations..

3.12 Force-Ductility Engineering Creep Compliance at Failure at 39.2F (4C)

3.12.1 Engineering creep compliance data are tabulated in Appendix L in Table L-1. Three determinations were made for each matrix cell replication.

3.12.1.1 Average coefficient of variation for Atlos rubber at all concentrations and both asphalts was 11.0 percent compared to 10.4 percent for the U.S. Rubber Reclaiming rubber.

3.12.1.2 Average coefficients of variation for each rubber type at all concentrations and for both asphalts are:

- TP044 - 12.3%
- TP027 - 12.3%
- 50/50 TP044/TP027 - 8.4%
- GT274 - 7.8%
- USRF - 7.8%
- 50/50 GT274/USRF - 15.6%

3.12.1.3 Average coefficients of variation for each rubber concentration for all rubber types and both asphalts are:

- 15% - 13.3%
- 20% - 9.1%
- 25% - 10.2%
- 30% - 9.6%

3.12.1.4 Average coefficient of variation for all mixtures containing AR4000 asphalt was 9.6 percent, and for the AR1000, 11.8 percent.

3.12.1.5 Variability of engineering creep compliance data as indicated by coefficient of variation does not appear to be influenced by rubber type, rubber concentration, or asphalt grade.

3.12.2 Reduced data are tabulated in Appendix L in Table L-2 and plotted in Figures L1 through L12. Each entry in Table L-2 is the mean of three values in Table L-1.

3.12.3 In order to satisfy variance homogeneity requirements, log log arctangent square root transformations of the data were required prior to analysis. Transformed data are tabulated in Appendix L in Table L-3 and plotted in Figures L13 through L24.

3.12.4 The ANOVA summary for engineering creep compliance at failure is tabulated in Table L-4.

3.12.4.1 All main effects and interactions were significant at the 0.01 level.

3.12.5 Analyses indicate that rubber type, rubber concentration, asphalt, and all interactions influence engineering creep compliance at failure of asphalt-rubber mixtures during the force-ductility test.

3.12.5.1 Effect of Rubber Type. Asphalt-rubber mixtures containing GT274 rubber had the highest engineering creep compliance at failure (0.1042 psi^{-1} overall average) and mixtures containing the 50-50 TP044/TP027 rubber, the lowest (0.0398 psi^{-1} overall average).

For asphalt-rubber mixtures containing Atlos rubber, mixtures containing large rubber particles (TPO44) have lower engineering creep compliance values (0.0440 psi^{-1} overall average) than mixtures containing the smaller TPO27 particles (0.0950 psi^{-1} overall average). The mixture of TPO44 and TPO27 had lower values than mixtures containing either of the two individual rubbers (0.0398 psi^{-1} overall average).

For mixtures containing U.S. Rubber Reclaiming rubber, the small USRF particles resulted in lower engineering creep compliance values (0.0744 psi^{-1} overall average) than mixtures containing the larger GT274 particles (0.1042 psi^{-1} overall average). The mixture of GT274 and USRF had average engineering creep compliance at failure (0.0944 psi^{-1} overall average) which was between that obtained for GT274 and USRF.

3.12.5.2 Effect of Rubber Concentration. Examination of Figures L3, L4, and L5 shows that for asphalt-rubber mixtures containing AR1000 asphalt and Atlos rubber, as rubber concentration increases, engineering creep compliance at failure decreases. This effect is present with Atlos mixtures containing AR4000 asphalt, but differences are not as great.

For asphalt-rubber mixtures containing U.S. Rubber Reclaiming rubber and AR1000 asphalt, as rubber concentration increases from 15 to 25 percent, engineering creep compliance at failure decreases, but then tends to remain the same at 30 percent rubber as seen in Figures L6, L7, and L8. Engineering creep compliance values for mixtures containing AR4000 asphalt do not decrease as much as for mixtures containing AR1000 asphalt as rubber concentration increases.

Two-way ANOVA by rubber type shows that for all rubbers investigated, rubber concentration is a significant effect on engineering creep compliance at failure results. Two-way ANOVA by asphalt type indicates that concentration is significant for both AR1000 and AR4000 asphalt.

3.12.5.3 Effect of Asphalt. Examination of Figures L3 through L12 shows that with one exception, asphalt-rubber mixtures containing AR1000 asphalt have higher mean engineering creep compliance at failure values than mixtures containing AR4000 asphalt for all rubber types investigated and all rubber concentrations. Differences in results between asphalts decrease as rubber concentration increases for all rubber types.

3.13 Force-Ductility True Creep Compliance at Failure at 39.2F (4C)

3.13.1 True creep compliance data are tabulated in Appendix M in Table M-1. Three determinations were made for each matrix cell replication.

3.13.1.1 Average coefficient of variation for Atlos rubber at all concentrations and both asphalts was 9.9 percent compared to 8.3 percent for the U.S. Rubber Reclaiming rubber.

3.13.1.2 Average coefficients of variation for each rubber type at all concentrations and for both asphalts are:

- TP044 - 11.4%
- TP027 - 11.5%
- 50/50 TP044/TP027 - 6.7%
- GT274 - 5.4%
- USRF - 7.6%
- 50/50 GT274/USRF - 12.4%

3.13.1.3 Average coefficients of variation for each rubber concentration for all rubber types and both asphalts are:

- 15% - 8.8%
- 20% - 8.8%
- 25% - 9.5%
- 30% - 9.6%

3.13.1.4 Average coefficient of variation for all mixtures containing AR4000 asphalt was 9.7 percent, and for the AR1000, 8.6 percent.

3.13.1.5 Variability of true creep compliance at failure data as indicated by coefficient of variation does not appear to be influenced by rubber particle size, rubber concentration, or asphalt grade.

3.13.2 Analyzed true creep compliance at failure data are tabulated in Appendix M in Table M-2 and plotted in Figures M1 through M12. Each entry in Table M-2 is the mean of three values from Table M-1.

3.13.3 The ANOVA summary for true creep compliance at failure data is tabulated in Table M-3.

3.13.3.1 All main effects and interactions are significant at the 0.01 level.

3.13.4 Analyses indicate that rubber type, rubber concentration, asphalt, and all interactions influence true creep compliance at failure of asphalt-rubber mixtures during the force-ductility test.

3.13.4.1 Effect of Rubber Type. Asphalt-rubber mixtures containing the 50/50 GT274/USRF rubber had the highest average true creep compliance at failure values (0.00412 psi^{-1} overall average) while the 50/50 TPO44/TPO27 rubber had the lowest (0.00227 psi^{-1} overall average).

For asphalt-rubber mixtures containing Atlos rubber, TPO44, and TPO27 mixtures had approximately the same average true creep compliance values (0.00329 psi^{-1} overall average for TPO44 compared to 0.00331 psi^{-1} for TPO27). The mixture of the two rubbers resulted in a lower value (0.00227 psi^{-1}) indicating a stiffer mixture.

The asphalt-rubber mixtures containing U.S. Rubber Reclaiming rubber had approximately the same average true creep compliance values (0.00308 psi^{-1} overall average for GT274, 0.00272 psi^{-1} for USRF, and 0.00320 psi^{-1} for the 50/50 GT274/USRF mixture).

3.13.4.2 Effect of Rubber Concentration. Examination of Figures M3, M4, and M5 shows that for mixtures containing Atlos rubber, as concentration increases, true creep compliance at failure decreases. The effect is greater with AR1000 than AR4000 asphalt.

For asphalt-rubber mixtures containing U.S. Rubber Reclaiming rubber, as concentration increases from 15 to 25 percent, true creep compliance at failure decreases, but, then, as seen in Figures M6, M7, and M8, tends to remain the same or slightly increase at 30 percent rubber. As with Atlos rubber, the effect is greater with AR1000 than the AR4000 asphalt.

Two-way ANOVA by rubber type shows that for all rubber types investigated, except for the 50-50 GR274/USRF mixture, concentration is a significant effect on true creep compliance at failure. Two-way ANOVA by asphalt type indicates that concentration is a significant effect for both AR1000 and AR4000.

3.13.4.3 Effect of Asphalt. Examination of Figures M3 through M12 shows that asphalt-rubber mixtures containing AR1000 asphalt have higher mean true creep compliance at failure values than mixtures containing AR4000 asphalt for all rubber types and concentrations. Differences in results decrease as rubber concentration increases for all rubber types indicating that at high rubber concentration, asphalt characteristics have a lesser effect on true creep compliance at failure than at lower rubber concentrations.

3.14 Force-Ductility Maximum True Creep Compliance at 39.2F (4C)

3.14.1 Maximum true creep compliance data are tabulated in Appendix N in Table N-1. Three determinations were made for each matrix cell replication.

3.14.1.1 Average coefficient of variation for Atlos rubber at all concentrations and both asphalts was 8.0 percent compared to 6.9 percent for the U.S. Rubber Reclaiming rubber.

3.14.1.2 Average coefficients of variation for each rubber type at all concentrations and for both asphalts are:

- TP044 - 8.8%
- TP027 - 9.7%
- 50/50 TP044/TP027 - 5.6%
- GT274 - 6.4%
- USRF - 5.0%
- 50/50 GT274/USRF - 9.2%

3.14.1.3 Average coefficients of variation for each rubber concentration for all rubber types and both asphalts are:

- 15% - 8.1%
- 20% - 7.2%
- 25% - 7.4%
- 30% - 7.0%

3.14.1.4 Average coefficient of variation for all mixtures containing AR4000 asphalt was 8.1 percent, and for the AR1000, 6.8 percent.

3.14.1.5 Variability of maximum true creep compliance data as indicated by coefficient of variation does not appear to be influenced by rubber particle size, rubber concentration, or asphalt grade.

3.14.2 Analyzed maximum true creep compliance data are tabulated in Appendix N in Table N-2 and plotted in Figures N1 through N12. Each entry in Table N-2 is the mean of three values in Table N-1.

3.14.3 The ANOVA summary for maximum true creep compliance data is tabulated in Table N-3.

3.14.3.1 All main effects and interactions are significant at the 0.01 level.

3.14.4 Analyses indicate that rubber type, rubber concentration, asphalt, and all interactions influence maximum true creep compliance of asphalt-rubber mixtures during the force-ductility test.

3.14.4.1 Effect of Rubber Type. Asphalt-rubber mixtures containing GT274 and the 50/50 GT274/USRF rubbers had the highest maximum true creep compliance values (0.00812 psi^{-1} overall average for GT274 and 0.00814 psi^{-1} for the 50/50 GT274/USRF mixture) while the 50/50 TPO44/TPO27 mixture had the lowest (0.00421 psi^{-1} overall average).

For asphalt-rubber mixtures containing Atlos rubber, TPO44 mixtures had lower average maximum true creep compliance than TPO27 mixtures (0.00505 psi^{-1} overall average for TPO44 compared to 0.00675 psi^{-1} for TPO27). The mixture of the two rubbers resulted in a the lowest average maximum true creep compliance (0.00421 psi^{-1} overall average).

For asphalt-rubber mixtures containing U.S. Rubber Reclaiming rubber, USRF mixtures had slightly lower average maximum true creep compliance (0.00730 psi^{-1} overall average) than the GT274 or 50/50 GT274/USRF rubbers (0.00812 psi^{-1} and 0.00814 psi^{-1} overall averages respectively).

3.14.4.2 Effect of Rubber Concentration. Examination of Figures N3, N4, and N5 show that for TPO44 and the 50/50 TPO44/TPO27 mixtures with AR1000 asphalt, as rubber concentration increases, maximum true creep compliance tends to decrease. For mixtures containing TPO27 rubber and AR1000 asphalt, maximum true creep compliance decrease as rubber concentration increases from 15 to 25 percent, but then increases at 30 percent. For mixtures containing AR4000 asphalt and Atlos rubber, maximum true creep compliance tend to remain constant or slightly increase as rubber percentage increases.

For mixtures containing U.S. Rubber Reclaiming rubber and AR1000 asphalt, as rubber concentration increases, maximum true creep compliance tend to remain approximately the same. Slight increases are noted for GT274 and USRF mixtures at 30 percent rubber. On the other hand, with AR4000 asphalt, as rubber concentration increases, maximum true creep compliance tends to increase.

Two-way ANOVA by rubber type shows that concentration is a significant effect on maximum true creep compliance.

Two-way ANOVA by asphalt shows that concentration is a significant effect for both AR1000 and AR4000 mixtures.

3.14.4.3 Effect of Asphalt. Examination of Figures N3 through N12 shows that with one exception, asphalt-rubber mixtures containing AR1000 asphalt have higher mean maximum true creep compliance than mixtures containing AR4000 asphalt for all rubber types and concentrations. Differences between asphalt types decrease as rubber concentration increases for all rubber types indicating that at higher rubber concentrations asphalt characteristics have a lesser effect on maximum true creep compliance than at lower concentrations.

Two-way ANOVA by rubber type shows that asphalt is a significant effect for all rubber types.

Two-way ANOVA by concentration shows that asphalt is a significant effect at all concentrations.

3.15 Force-Ductility Time to Maximum True Creep Compliance

3.15.1 Time to maximum true creep compliance data are tabulated in Appendix O in Table O-1. Three determinations were made for each matrix cell replication.

3.15.1.1 Average coefficient of variation for Atlos rubber at all concentrations and both asphalts was 4.5 percent compared to 5.3 percent for the U.S. Rubber Reclaiming rubber.

3.15.1.2 Average coefficients of variation for each rubber type at all concentrations and for both asphalts are:

- TP044 - 6.1%
- TP027 - 2.2%
- 50/50 TP044/TP027 - 5.3%
- GT274 - 3.9%
- USRF - 5.9%
- 50/50 GT274/USRF - 6.1%

3.15.1.3 Average coefficients of variation for each rubber concentration for all rubber types and both asphalts are:

- 15% - 3.8%
- 20% - 4.3%
- 25% - 5.1%
- 30% - 6.4%

3.15.1.4 Average coefficient of variation for all mixtures containing AR4000 asphalt was 4.5 percent, and for the AR1000, 5.3 percent.

3.15.1.5 Variability of time to maximum true creep compliance data as indicated by coefficient of variation is low (4.9 percent overall average) and does not appear to be influenced by rubber particle size, rubber concentration, or asphalt grade.

3.15.2 Analyzed time to maximum true creep compliance data are tabulated in Appendix N in Table O-2 and plotted in Figures O1 through O12. Each entry in Table O-2 is the mean of three values in Table O-1.

3.15.3 The ANOVA summary for time to maximum true creep compliance data is tabulated in Table O-3.

3.15.3.1 Rubber, concentration, asphalt, rubber-concentration interaction, and concentration-asphalt interaction are significant effects at the 0.01 level. Rubber-asphalt and rubber-concentration-asphalt interaction are not significant at the 0.05 level.

3.15.4 Analyses indicate that rubber type, rubber concentration, asphalt and several interactions influence time to reach maximum true creep compliance of asphalt-rubber mixtures during the force-ductility test.

3.15.4.1 Effect of Rubber Type. Average time to maximum true creep compliance failure for asphalt-rubber mixtures containing Atlos rubber were approximately the same (9.3 minutes overall average for TP044, 9.9 minutes for TP027, and 9.4 minutes for the 50/50 TP044/TP027 mixture). Average results for U.S. Rubber Reclaiming mixtures were also approximately the same (11.4 minutes overall average for GT274, 11.1 minutes for USRF, and 11.3 minutes for the 50/50 GT274/USRF mixture).

3.15.4.2 Effect of Rubber Concentration. Examination of Figures O3 through O8 shows for all rubber types and both asphalts, that as rubber concentration increases, time to maximum true creep compliance decreases (13.2 minutes overall mean at 15 percent rubber compared to 8.1 minutes for 30 percent rubber).

Two-way ANOVA by rubber type shows that concentration is a significant effect for all rubber types investigated.

Two-way ANOVA by asphalt shows that concentration is a significant effect for both AR1000 and AR4000 asphalts.

3.15.4.3 Effect of Asphalt. Examination of Figures O3 through O12 shows that with one exception time to maximum true creep compliance of asphalt-rubber mixtures containing AR4000 is slightly higher than for mixtures containing AR1000 asphalt (10.9 minute overall average for AR4000 asphalt compared to 9.9 minutes for the AR1000 mixtures).

Two-way ANOVA by rubber type shows that asphalt is a significant effect for all rubber types except the 50/50 GT274/USRF mixture.

Two-way ANOVA by concentration shows that asphalt is a significant effect at all concentrations.

3.16 Sliding Plate Apparent Viscosity at 32F (0C)

3.16.1 Measured and analyzed sliding plate apparent viscosity data are tabulated in Appendix P in Table P-1 and plotted in Figures P1 through P12.

3.16.1.1 Average coefficient of variation for Atlos rubber at all concentrations and both asphalts was 26.0 percent compared to 23.9 percent for the U.S. Rubber Reclaiming rubber.

3.16.1.2 Average coefficients of variation for each rubber type at all concentrations and for both asphalts are:

- TP044 - 31.5%
- TP027 - 20.1%
- 50/50 TP044/TP027 - 25.9%
- GT274 - 16.7%
- USRF - 30.6%
- 50/50 GT274/USRF - 24.5%

3.16.1.3 Average coefficients of variation for each rubber concentration for all rubber types and both asphalts are:

- 15% - 16.9%
- 20% - 30.7%
- 25% - 22.1%
- 30% - 30.0%

3.16.1.4 Average coefficient of variation for all mixtures containing AR4000 asphalt was 24.2 percent, and for the AR1000, 25.7 percent.

3.16.1.5 Variability of measured sliding plate apparent viscosity data as indicated by coefficient of variation does not appear to be influenced by rubber particle size, rubber concentration, or asphalt grade.

3.16.2 The ANOVA summary for sliding plate apparent viscosity is tabulated in Table P-2.

3.16.2.1 Rubber, asphalt, and all interactions are significant effects at the 0.01 level. Concentration is significant at the 0.05 level but not at 0.01.

3.16.3 Analyses indicate that rubber type, rubber concentration, asphalt, and all interactions influence apparent viscosity of asphalt-rubber mixtures as measured by the sliding plate microviscometers.

3.16.3.1 <u>Effect of Rubber Type</u>. Asphalt-rubber mixtures containing TP044 rubber had the highest average apparent viscosity (6.21 x 10^9 poise overall average) while the 50/50 GT274/USRF rubber had the lowest (2.22 x 10^9 poise overall average). For asphalt-rubber mixtures containing Atlos rubber, data indicate that as particle size increases, apparent viscosity increases (3.37 x 10^9 poise overall average for TP027 compared to 6.21 x 10^9 poise for TP044).

For mixtures containing U.S. Rubber Reclaiming rubber, average apparent viscosity is not greatly affected by rubber particle size (2.29 x 10^9 poise overall average for GT274, 2.63 x 10^9 poise for USRF, and 2.22 x 10^9 poise for the 50/50 GT274/USRF mixture).

3.16.3.2 <u>Effect of Rubber Concentration</u>. Examination of Figures P3, P4, and P5 show for mixtures containing AR1000 asphalt and Atlos rubber, that as rubber concentration increases, apparent viscosity tends to increase. This trend is not noted with the AR4000 asphalt.

Examination of Figures P6, P7, and P8 indicate for mixtures containing U.S. Rubber Reclaiming rubber, that as rubber concentration increases, apparent viscosity remains approximately the same for mixtures containing both asphalts.

Two-way ANOVA by rubber type shows that concentration is a significant effect for TP044, 50/50 TP044/TP027 mixture, GT274, and the 50/50 GT274/USRF mixture.

Two-way ANOVA by asphalt shows that concentration is a significant effect for both AR1000 and AR4000 asphalts.

3.16.3.3 Effect of Asphalt. Examination of Figures P3, P4, and P5 shows that for mixtures containing Atlos rubber, those with AR4000 asphalt have higher apparent viscosity than mixtures containing AR1000 asphalt (6.52×10^9 poise overall average for AR4000 compared to 3.66×10^9 poise for AR1000).

Figures P6, P7, and P8 show that for mixtures containing U.S. Rubber Reclaiming rubber, those with AR4000 asphalt have slightly higher apparent viscosities than those containing AR1000 asphalt (2.71×10^9 poise overall average for AR4000 compared to 2.04×10^9 poise for AR1000).

Two-way ANOVA by rubber type shows that asphalt is a significant effect for all mixtures except those containing USRF and the 50/50 GT274/USRF mixture.

Two-way ANOVA by concentration shows that asphalt is a significant effect at all concentrations investigated.

3.17 Sliding Plate First Cycle Creep (30 min.) at 32F (0C)

3.17.1 Measured and analyzed sliding plate first cycle creep data are tabulated in Appendix Q in Table Q-1 and plotted in Figures Q1 through Q12.

3.17.1.1 Average coefficient of variation for Atlos rubber at all concentrations and both asphalts was 13.2 percent compared to 15.1 percent for the U.S. Rubber Reclaiming rubber.

3.17.1.2 Average coefficients of variation for each rubber type at all concentrations and for both asphalts are:

- TP044 - 11.8%
- TP027 - 14.3%
- 50/50 TP044/TP027 - 13.6%
- GT274 - 13.3%
- USRF - 23.7%
- 50/50 GT274/USRF - 8.4%

3.17.1.3 Average coefficients of variation for each rubber concentration for all rubber types and both asphalts are:

- 15% - 15.7%
- 20% - 12.9%
- 25% - 14.8%
- 30% - 13.3%

3.17.1.4 Average coefficient of variation for all mixtures containing AR4000 asphalt was 14.3 percent and for the AR1000, 13.2 percent.

3.17.1.5 Variability of measured sliding plate first cycle creep (30 min.) data as indicated by coefficient of variation does not appear to be influenced by rubber particle size, rubber concentration, or asphalt grade.

3.17.2 The ANOVA summary for sliding plate first cycle creep (30 min.) is tabulated in Table Q-2.

3.17.2.1 Rubber, concentration, asphalt, rubber-concentration interaction, and concentration-asphalt interaction are significant effects at the 0.01 level. Rubber-asphalt and rubber-concentration-asphalt interactions are not significant at the 0.05 level.

3.17.3 Analyses indicate that rubber type, rubber concentration, asphalt and several interactions influence first cycle sliding plate creep (30 min.) of asphalt-rubber mixtures.

3.17.3.1 <u>Effect of Rubber Type</u>. Asphalt-rubber mixtures containing the 50-50 GT274/USRF rubber had the highest 30 minute first cycle creep (648 microns overall average) while the TPO44 mixtures had the lowest (305 micron overall average). Data indicate that in general, as rubber particle size increases, for both Atlos and U.S. Rubber Reclaiming rubber, 30 minute first cycle creep decreases.

3.17.3.2 Effect of Rubber Concentration. The effects of rubber concentration on 30 minute first cycle creep vary depending on rubber type. For TPO44 mixtures, first cycle creep does not appear to be affected by rubber concentration for either AR1000 or AR4000 asphalt. TPO27 mixtures containing AR4000 asphalt tend to creep more as rubber concentration increases whereas mixtures containing AR1000 asphalt do not seem to be affected by concentration. The same trends noted with TPO27 are noted for the 50/50 TPO44/TPO27 rubber. Above trends can be seen in Figures Q3, Q4, and Q5.

All mixtures containing U.S. Rubber Reclaiming rubber and AR4000 asphalt tend to creep more as rubber concentration increases (288 micron average at 15 percent rubber compared to 779 microns at 30 percent rubber). U.S. Rubber Reclaiming mixtures containing AR1000 asphalt exhibit the same trend (599 micron overal average at 15 percent rubber, compared to 840 microns at 30 percent) but not to the extent as with AR4000 mixtures. Above trends can be seen in Figures Q6, Q7, and Q8.

Two-way ANOVA by rubber type shows that concentration is a significant effect for all rubber types except TPO27.

Two-way ANOVA by asphalt type shows that concentration is a significant effect for both AR1000 and AR4000 asphalts.

3.17.3.3 Effect of Asphalt. Examination of Figures Q3 through Q12 shows that with one exception mixtures containing AR4000 asphalt experienced less 30 minute first cycle creep than mixtures containing AR1000 asphalt (383 micron overall average for AR4000 compared to 592 microns for AR1000).

Two-way ANOVA by rubber type shows that asphalt is a significant effect for all rubber types investigated.

Two-way ANOVA by concentration shows that asphalt is a significant effect for all concentrations investigated.

3.18 Sliding Plate First Cycle Recovery (30 min.) at 32F (0C)

3.18.1 Measured and analyzed sliding plate first cycle recovery data are tabulated in Appendix R in Table R-1 and plotted in Figures R1 through R12.

3.18.1.1 Average coefficient of variation for Atlos rubber at all concentrations and both asphalts was 13.1 percent compared to 16.8 percent for the U.S. Rubber Reclaiming rubber.

3.18.1.2 Average coefficients of variation for each rubber type at all concentrations and for both asphalts are:

- TP044 - 11.1%
- TP027 - 15.5%
- 50/50 TP044/TP027 - 20.0%
- GT274 - 15.4%
- USRF - 17.2%
- 50/50 GT274/USRF - 16.43

3.18.1.3 Average coefficients of variation for each rubber concentration for all rubber types and both asphalts are:

- 15% - 20.4%
- 20% - 15.6%
- 25% - 13.0%
- 30% - 10.9%

3.18.1.4 Average coefficient of variation for all mixtures containing AR4000 asphalt was 16.6 percent and for the AR1000, 19.2 percent.

3.18.1.5 Variability of measured sliding plate first cycle recovery (30 min.) data as indicated by coefficient of variation appears not to be influenced by rubber particle size, less for high rubber concentrations than for low, and not influenced by asphalt grade.

3.18.2 The ANOVA summary for sliding plate first cycle recovery (30 min.) is tabulated in Table R-2.

3.18.2.1 Rubber, concentration, asphalt, and rubber-concentration interaction, are significant effects at the 0.01 level. All other interactions are not significant at the 0.05 level.

3.18.3 Analyses indicate that rubber type, rubber concentration, apshalt, and the rubber-concentration interaction influence first cycle sliding plate recovery (30 min.) of asphalt-rubber mixtures.

3.18.3.1 Effect of Rubber Type. Asphalt-rubber mixtures containing the 50/50 GT274/USRF rubber had the highest average 30 minute first cycle recovery (249 micron overall average) while the 50/50 TP044/TP027 mixtures had the lowest (140 micron overall average). Particle size within Atlos or U.S. Rubber Reclaiming rubbers does not appear to influence 30 minute first cycle recovery. U.S. Rubber Reclaiming mixtures had higher recovery (240 micron overall average) than Atlos mixtures (151 micron overall average).

3.18.3.2 Effect of Rubber Concentration. Examination of Figures R3 through R8 show that as rubber concentration increases 30 minute first cycle recovery increases for all rubber types and both asphalts (128 micron overall average at 15 percent rubber compared to 280 microns at 30 percent).

Two-way ANOVA by rubber type shows that concentration is a significant effect for all rubber types investigated.

Two-way ANOVA by asphalt shows that concentration is a significant effect for both AR1000 and AR4000 asphalts.

3.18.3.3 Effect of Asphalt. Examination of Figures R3 through R12 show that asphalt-rubber mixtures containing AR1000 asphalt experience more 30 minute first cycle recovery than mixtures containing AR4000 asphalt for all rubber types and concentrations.

Two-way ANOVA by rubber type shows that asphalt is a significant effect for all rubber types.

Two-way ANOVA by concentration shows that asphalt is a significant effect for all concentrations investigated.

3.19 Sliding Plate Second Cycle Creep (30 min.) at 32F (0C)

3.19.1 Measured and analyzed sliding plate second cycle creep data are tabulated in Appendix S in Table S-1 and plotted in Figures S1 through S12.

3.19.1.1 Average coefficient of variation for Atlos rubber at all concentrations and both asphalts was 9.1 percent compared to 10.8 percent for the U.S. Rubber Reclaiming rubber.

3.19.1.2 Average coefficients of variation for each rubber type at all concentrations and for both asphalts are:

- TP044 - 9.2%
- TP027 - 7.8%
- 50/50 TP044/TP027 - 10.4%
- GT274 - 10.2%
- USRF - 11.8%
- 50/50 GT274/USRF - 10.2%

3.19.1.3 Average coefficients of variation for each rubber concentration for all rubber types and both asphalts are:

- 15% - 8.8%
- 20% - 13.4%
- 25% - 12.0%
- 30% - 5.7%

3.19.1.4 Average coefficient of variation for all mixtures containing AR4000 asphalt was 10.1 percent, and for the AR1000, 9.8 percent.

3.19.1.5 Variability of measured sliding plate second cycle creep (30 min.) data as indicated by coefficient of variation does not appear to be influenced by rubber particle size, rubber concentration, or asphalt grade.

3.19.2 The ANOVA summary for sliding plate second cycle creep (30 min.) is tabulated in Table S-2.

3.19.2.1 All main effects and interactions are significant at the 0.01 level except for the rubber-concentration-asphalt interaction which is significant at the 0.05 level but not at the 0.01.

3.19.3 Analyses indicate that rubber type, rubber concentration, asphalt, and all interactions influence second cycle sliding plate creep (30 min.) of asphalt-rubber mixtures.

3.19.3.1 Effect of Rubber Type. Asphalt-rubber mixtures containing 50/50 GT274/USRF rubber had the highest average 30 minute second cycle creep (479 micron overall average) while the TPO44 mixtures had the lowest (230 micron overall average). Data indicate that as rubber particle size increases, for both Atlos and U.S. Rubber Reclaiming rubbers, 30 minute second cycle creep may slightly decrease.

3.19.3.2 Effect of Rubber Concentration. Examination of Figures S3, S4, and S5 indicates for asphalt-rubber mixtures containing Atlos rubber and AR4000 asphalt, that as rubber concentration increases, 30 minute second cycle creep increases, while with AR1000 asphalt, the amount of creep remains approximately the same at all rubber concentrations.

Examination of Figures S6, S7, and S8 shows for asphalt-rubber mitures containing U.S. Rubber Reclaiming rubber and both asphalts, that as rubber concentration increases, 30 minute second cycle creep increases (320 micron overall average at 15 percent rubber compared to 622 microns at 30 percent).

Two-way ANOVA by rubber type shows that concentration is a significant effect for all rubber types except TPO44.

Two-way ANOVA by asphalt shows that concentration is a significant effect for both AR1000 and AR4000 asphalts.

3.19.3.3 Effect of Asphalt. Examination of Figures S3 through S12 shows that with one exception mixtures containing AR4000 asphalt experienced less 30 minute second cycle creep than mixtures containing AR1000 asphalt (265 micron overall average for AR4000 compared to 451 microns for AR1000).

Two-way ANOVA by rubber type indicates asphalt is a significant effect for all rubber types.

Two-way ANOVA by concentration indicates asphalt is a significant effect at all concentrations investigated.

3.20 Sliding Plate Second Cycle Recovery (30 min.) at 32F (0C)

3.20.1 Measured and analyzed sliding plate second cycle recovery (30 min.) data are tabulated in Appendix T in Table T-1 and plotted in Figures T1 through T12.

3.20.1.1 Average coefficient of variation for Atlos rubber at all concentrations and both asphalts was 11.5 percent compared to 16.2 percent for the U.S. Rubber Reclaiming rubber.

3.20.1.2 Average coefficients of variation for each rubber type at all concentrations and for both asphalts are:

- TP044 - 9.8%
- TP027 - 9.9%
- 50/50 TP044/TP027 - 13.3%
- GT274 - 11.6%
- USRF - 13.8%
- 50/50 GT274/USRF - 20.0%

3.20.1.3 Average coefficients of variation for each rubber concentration for all rubber types and both asphalts are:

- 15% - 16.5%
- 20% - 12.3%
- 25% - 17.5%
- 30% - 8.9%

3.20.1.4 Average coefficient of variation for all mixtures containing AR4000 asphalt was 15.3 percent and for the AR1000 10.9 percent.

3.20.1.5 Variability of measured sliding plate second cycle recovery (30 min.) data as indicated by coefficient of variation appears to be:

- not influenced by particle size
- possibly less for high rubber concentration than for low
- less for AR1000 than for AR4000 asphalt cement

3.20.2 The ANOVA summary for sliding plate second cycle recovery (30 min.) is tabulated in Table T-2.

3.20.2.1 Rubber, concentration, asphalt, and the rubber-concentration interaction are significant effects at the 0.01 level. The rubber-concentration-asphalt interaction is significant at the 0.05 level but not at 0.01. Rubber-asphalt and concentration-asphalt interactions are not significant at the 0.05 level.

3.20.3 Analyses indicate that rubber type, rubber concentration, asphalt, and several interactions influence second cycle sliding plate recovery (30 min.) of asphalt-rubber mixtures.

3.20.3.1 Effect of Rubber Type. Asphalt-rubber mixtures containing the 50-50 GT274/USRF rubber had the highest average 30 minute second cycle recovery (275 micron overall average) while the TPO44 mixtures had the lowest (141 micron overall average). Particle size within Atlos or U.S. Rubber Reclaiming rubbers does not appear to affect 30 minute second cycle recovery. U.S. Rubber Reclaiming mixtures had higher recovery values (255 micron overall average) than Atlos mixtures (156 micron overall average).

3.20.3.2 Effect of Rubber Concentration. Examination of Figures T3 through T8 shows that as rubber concentration increases, 30 minute second cycle recovery increases for all rubber types and both asphalts (131 micron overall average at 15 percent rubber compared to 295 microns at 30 percent).

Two-way ANOVA by rubber type shows that concentration is a significant effect for all rubber types investigated.

Two-way ANOVA by asphalt shows that concentration is a significant effect for both AR1000 and AR4000 asphalts.

3.20.3.3 Effect of Asphalt. Examination of Figures T3 through T12 show asphalt-rubber mixtures containing AR1000 asphalt experience more 30 minute second cycle recovery than mixtures containing AR4000 asphalt for all rubber types and concentrations (144 micron overall average for AR4000 compared to 266 microns for AR1000).

Two-way ANOVA by rubber type shows that asphalt is a significant effect for all rubber types investigated.

Two-way ANOVA by concentration shows that asphalt is a significant effect for all concentrations investigated.

3.21 Sliding Plate Second Cycle Recovery (20 hour) at 32F (0C)

3.21.1 Measured and analyzed sliding plate second cycle recovery (20 hour) data are tabulated in Appendix U in Table U-1 and plotted in Figures U1 through U12.

3.21.1.1 Average coefficient of variation for Atlos rubber at all concentrations and both asphalts was 21.3 percent compared to 29.2 percent for the U.S. Rubber Reclaiming rubber.

3.21.1.2 Average coefficients of variation for each rubber type at all concentrations and for both asphalts are:

- TP044 - 22.5%
- TP027 - 19.0%
- 50/50 TP044/TP027 - 22.6%
- GT274 - 22.4%
- USRF - 40.7%
- 50/50 GT274/USRF - 24.5%

3.21.1.3 Average coefficients of variation for each rubber concentration for all rubber types and both asphalts are:

- 15% - 39.0%
- 20% - 31.5%
- 25% - 19.5%
- 30% - 13.0%

3.21.1.4 Average coefficient of variation for all mixtures containing AR4000 asphalt was 31.4 percent and for the AR1000, 19.1 percent.

3.21.1.5 Variability of measured sliding plate second cycle recovery (20 hour) data as indicated by coefficient of variation appears to be:

- not influenced by rubber particle size
- less for high rubber concentration than for low
- less for the AR1000 than the AR4000 asphalt cement

3.21.2 The ANOVA summary for sliding plate second cycle recovery (20 hour) is tabulated in Table U-2.

3.21.2.1 Rubber, concentration, asphalt, and rubber-concentration interaction are significant effects at the 0.01 level. The other interactions are not significant at the 0.05 level.

3.21.3 Analyses indicate that rubber type, rubber concentration, asphalt and the rubber-concentration interaction influence second cycle sliding plate recovery (20 hour) of asphalt-rubber mixtures.

3.21.3.1 Effect of Rubber Type. Asphalt-rubber mixtures containing USRF rubber had the highest average 20 hour second cycle recovery (493 micron overall average) while the TPO44 and 50/50 TPO44/TPO27 rubbers had the lowest (219 micron overall average for each). Particle size within Atlos rubber mixtures does not appear to influence 20 hour recovery at 15 and 20 percent rubber concentrations, but differences in mean values were noted at 25 and 30 percent concentrations.

For U.S. Rubber Reclaiming mixtures, as particle size increases 20 hour recovery decreases. U.S. Rubber Reclaiming mixtures had higher 20 hour recovery values (438 micron overall average) than Atlos mixtures (233 micron overall average).

3.21.3.2 Effect of Rubber Concentration. Examination of Figures U3 through U8 shows that as rubber concentration increases, 20 hour second cycle recovery increases for all rubber types and both asphalts (219 micron overall average at 15 percent rubber compared to 459 microns at 30 percent).

Two-way ANOVA by rubber type shows that concentration is a significant effect for all rubber types investigated.

Two-way ANOVA by asphalt shows that concentration is a significant effect for both AR1000 and AR4000 asphalts.

3.21.3.3 Effect of Asphalt. Examination of Figures U3 through U12 shows that asphalt-rubber mixtures containing AR1000 asphalt experience higher 20 hour second cycle recoveries than mixtures containing AR4000 asphalt for all rubber types and concentrations (252 micron overall average for AR4000 compared to 418 microns for AR1000).

Two-way ANOVA by rubber type shows that asphalt is a significant effect for all rubber types investigated.

Two-way ANOVA by concentration shows that asphalt is a significant effect at all concentrations investigated.

3.22 Sliding Plate Second Cycle Recovery (20 hour minus 30 min.) at 32F (0C)

3.22.1 Measured and analyzed sliding plate second cycle recovery (20 hour minus 30 min.) data are tabulated in Appendix V in Table V-1 and plotted in Figures V1 through V12.

3.22.1.1 Average coefficient of variation for Atlos rubber at all concentrations and both asphalts was 61.9 percent compared to 61.6 percent for the U.S. Rubber Reclaiming rubber.

3.22.1.2 Average coefficients of variation for each rubber type at all concentrations and for both asphalts are:

- TP044 - 62.0%
- TP027 - 62.9%
- 50/50 TP044/TP027 - 60.8%
- GT274 - 58.3%
- USRF - 71.9%
- 50/50 GT274/USRF - 54.7%

3.22.1.3 Average coefficients of variation for each rubber concentration for all rubber types and both asphalts are:

- 15% - 95.0%
- 20% - 62.7%
- 25% - 53.7%
- 30% - 35.6%

3.22.1.4 Average coefficient of variation for all mixtures containing AR4000 asphalt was 68.9 percent and for the AR1000, 54.7 percent.

3.22.1.5 Variability of measured sliding plate second cycle recovery (20 hour minus 30 min.) data as indicated by coefficient of variation appears to be:

- not influenced by rubber particle size
- less for high rubber concentrations than for low
- less for the AR1000 than the AR4000 asphalt cement

3.22.2 The ANOVA summary for sliding plate second cycle recovery (20 hour minus 30 min.) is tabulated in Table V-2.

3.22.2.1 Rubber, concentration, and asphalt are significant effects at the 0.01 level. Rubber-concentration interaction is significant at the 0.05 level but not at the 0.01. The other interactions are not significant at the 0.05 level.

3.22.3 Analyses indicate that rubber type, rubber concentration, asphalt and the rubber-concentration interaction influence second cycle sliding plate recovery (20 hour minus 30 minute) of asphalt-rubber mixtures.

3.22.3.1 Effect of Rubber Type. Asphalt-rubber mixtures containing USRF rubber had the highest recovery between 30 minutes and 20 hours (240 micron overall average) while the 50-50 TPO44/TPO27 rubber had the lowest (64 micron overall average). Particle size within Atlos rubber does not appear to affect data. For U.S. Rubber Reclaiming mixtures, as particle size increases, 20 hour minus 30 minute recovery appears to decrease (240 micron overall average for USRF mixtures compared to 140 microns for GT274).

U.S. Rubber Reclaiming mixtures had higher 20 hour minus 30 minute recovery values (183 micron overall average) than Atlos mixtures (78 micron overall average).

3.22.3.2 Effect of Rubber Concentration. Examination of Figures V3 through V12 shows that consistent effects due to rubber concentration are not noted. With several mixtures, as concentration increases, 20 hour minus 30 minute recovery tends to increase, while with other mixtures, recovery tends to decrease.

Two-way ANOVA by rubber type shows that concentration is a significant effect only for TPO44 and 50/50 GT274/USRF rubbers.

Two-way ANOVA by asphalt shows that concentration is a significant effect only for AR4000 asphalt.

3.22.3.3 Effect of Asphalt. Examination of Figures V3 through V12 shows, that for most asphalt-rubber mixtures, mixtures which contained AR1000 asphalt had higher 20 hour minus 30 minute second cycle recovery than mixtures containing AR4000 asphalt (109 micron overall average for AR4000 compared to 153 microns for AR1000).

Two-way ANOVA by rubber type shows that asphalt is a significant effect only for TPO27 rubber.

Two-way ANOVA by concentration shows that asphalt is a significant effect only at 20 percent rubber.

3.23 Sliding Plate Elastic Rebound at 32F (0C)

3.23.1 Measured and analyzed sliding plate elastic rebound data are tabulated in Appendix W in Table W-1 and plotted in Figures W1 through W12.

3.23.1.1 Average coefficient of variation for Atlos rubber at all concentrations and both asphalts was 10.6 percent compared to 19.0 percent for the U.S. Rubber Reclaiming rubber.

3.23.1.2 Average coefficients of variation for each rubber type at all concentrations and for both asphalts are:

- TP044 - 6.8%
- TP027 - 11.6%
- 50/50 TP044/TP027 - 12.4%
- GT274 - 17.6%
- USRF - 16.4%
- 50/50 GT274/USRF - 15.1%

3.23.1.3 Average coefficients of variation for each rubber concentration for all rubber types and both asphalts are:

- 15% - 16.4%
- 20% - 13.2%
- 25% - 16.7%
- 30% - 12.9%

3.23.1.4 Average coefficient of variation for all mixtures containing AR4000 asphalt was 12.5 percent and for the AR1000, 14.2 percent.

3.23.1.5 Variability of measured sliding plate elastic rebound data as indicated by coefficient of variation appears to be:

- less for Atlos rubber than U.S. Rubber Reclaiming,
- not influenced by rubber concentration, and
- not influenced by asphalt cement.

3.23.2 The ANOVA summary for sliding plate elastic rebound is tabulated in Table W-2.

3.23.2.1 Rubber, concentration, and asphalt are significant effects at the 0.01 level. All two-way interactions are significant at the 0.05 level but not at 0.01. The three-way interaction is not significant at the 0.05 level.

3.23.3 Analyses indicate that rubber type, rubber concentration, asphalt and several interactions influence sliding plate elastic rebound of asphalt-rubber mixtures.

3.23.3.1 Effect of Rubber Type. Asphalt-rubber mixtures containing TPO44 had the highest percent rebound (47.8 percent average) while mixtures containing U.S. Rubber Reclaiming rubber had the lowest (36.0 percent average for GT274, 36.6 percent for USRF, and 36.8 percent for the 50/50 GT274/USRF rubber).

For Atlos rubber, smaller rubber particles (TPO27) resulted in less rebound than the larger TPO44 rubber (40.4 percent for TPO27 compared to 47.8 percent for TPO44).

3.23.3.2 Effect of Rubber Concentration. Examination of Figures W3 through W8 shows that except for the 50/50 TPO44/TPO27 mixtures as rubber concentration increases percent rebound tends to increase (32.3 percent average at 15 percent rubber compared to 48.0 percent at 30 percent).

Two-way ANOVA by rubber type shows that concentration is a significant effect for all rubber types.

3.23.3.3 Effect of Asphalt. Examination of Figures W3 through W12 shows that for mixtures containing U.S. Rubber Reclaiming rubber, AR1000 mixtures experience more rebound than mixtures containing AR4000 asphalt (40.9 percent average for AR1000 compared to 32.0 percent for AR4000). For mixtures containing Atlos rubber, lesser differences exist in percent rebound of mixtures containing AR4000 and AR1000 asphalt (45.7 percent average for AR1000 compared to 43.9 percent for AR4000).

Two-way ANOVA by rubber type shows that asphalt is a significant effect for all rubbers except TPO44 and TPO27.

Two-way ANOVA by concentration shows that asphalt is significant at 15 and 25 percent rubber concentrations, but not at 20 and 30 percent.

3.24 Sliding Plate First Cycle Creep Coefficient S_m

3.24.1 Calculated creep coefficient S_m data are tabulated in Appendix X in Table X-1.

3.24.1.1 Average coefficient of variation for Atlos rubber at all concentrations and both asphalts was 30.0 percent compared to 30.5 percent for the U.S. Rubber Reclaiming rubber.

3.24.1.2 Average coefficients of variation for each rubber type at all concentrations and for both asphalts are:

- TP044 - 40.2%
- TP027 - 17.5%
- 50/50 TP044/TP027 - 37.6%
- GT274 - 19.5%
- USRF - 63.7%
- 50/50 GT274/USRF - 14.9%

3.24.1.3 Average coefficients of variation for each rubber concentration for all rubber types and both asphalts are:

- 15% - 40.2%
- 20% - 26.2%
- 25% - 22.3%
- 30% - 32.4%

3.24.1.4 Average coefficient of variation for all mixtures containing AR4000 asphalt was 41.7 percent and for the AR1000 22.8 percent.

3.24.1.5 Variability of calculated creep coefficient S_m data as indicated by coefficient of variation appears to vary widely with rubber type and concentration, but without exhibiting any trends with respect to particle size or increasing concentration. Variability of data for AR4000 mixtures is greater than that of AR1000 mixtures.

3.24.2 Numerous attempts were made to transform the creep coefficient S_m data in order to comply with variance homogeneity requirements, but all were unsuccessful. Therefore, ANOVA could not be performed with the data. The following discussion is based only on average data from Table X-1. Data were not plotted.

3.24.2.1 Average creep coefficient S_m for asphalt-rubber mixtures containing Atlos rubber is 0.126 compared to 0.227 for U.S. Rubber Reclaiming rubber mixtures. Average creep coefficient S_m does not vary widely (Atlos - 0.135 for TP044, 0.127 for TP027, and 0.115 for the 50/50 TP044/TP027 mixture; U.S. Rub- ber Reclaiming - 0.200 for GT274, 0.264 for USRF, and 0.216 for the 50/50 GT274/USRF mixture).

3.24.2.2 For Atlos rubber mixtures, as rubber concentration increases, creep coefficient S_m tends to increase (0.099 overall average at 15 percent rubber compared to 0.187 at 30 percent rubber). Creep coefficients S_m for asphalt-rubber mixtures containing U.S. Rubber Reclaiming rubber do not appear to be influenced by rubber concentration to the extent as Atlos rubber mixtures (0.246 overall average at 15 percent rubber compared to 0.253 at 30 percent).

3.24.2.3 Average creep coefficient S_m for mixtures containing AR4000 is 0.157 compared to 0.195 for AR1000.

3.25 Sliding Plate First Cycle Creep Coefficient b

3.25.1 Calculated and analyzed creep coefficient b data are tabulated in Appendix Y in Table Y-1.

3.25.1.1 Average coefficient of variation for Atlos rubber at all concentrations and both asphalts was 27.5 percent compared to 37.6 percent for the U.S. Rubber Reclaiming rubber.

3.25.1.2 Average coefficients of variation for each rubber type at all concentrations and for both asphalts are:

- TP044 - 14.8%
- TP027 - 31.8%
- 50/50 TP044/TP027 - 36.3%
- GT274 - 37.8%
- USRF - 47.8%
- 50/50 GT274/USRF - 27.2%

3.25.1.3 Average coefficients of variation for each rubber concentration for all rubber types and both asphalts are:

- 15% - 48.0%
- 20% - 34.5%
- 25% - 27.5%
- 30% - 20.2%

3.25.1.4 Average coefficient of variation for all mixtures containing AR4000 asphalt was 32.2 percent and for the AR1000, 33.1 percent.

3.25.1.5 Variability of calculated creep coefficient b data as indicated by coefficient of variation is lowest for TPO44 mixtures, but otherwise does not appear to be influenced by rubber type, tends to decrease as rubber concentration increases, and does not appear to be influenced by asphalt type.

3.25.2 The ANOVA summary for creep coefficient b data is tabulated in Table Y-2.

3.25.2.1 Rubber and concentration are significant at the 0.01 level. Rubber-concentration interaction and rubber-asphalt interaction are significant at the 0.05 level but not at 0.01. Asphalt and other interactions are not significant at the 0.05 level.

3.25.3 Analysis indicates that rubber type, concentration and two interactions influence creep coefficient b data.

3.25.3.1 Effect of Rubber Type. Asphalt-rubber mixtures containing the 50/50 TPO44/TPO27 rubber mixture had the highest creep coefficient b (0.265 overall average) while GT274 mixtures had the lowest (0.157 overall average).

Average creep coefficient b for Atlos rubber mixtures was 0.228 compared to 0.171 for U.S. Rubber Reclaiming mixtures.

3.25.3.2 Effect of Rubber Concentration. For Atlos rubber mixtures lowest creep coefficient b was at 25 percent rubber (0.130 average) and highest at 30 percent rubber (0.262 average).

For U.S. Rubber Reclaiming mixtures, as concentration increases, creep coefficient b increases (0.139 average at 15 percent rubber compared to 0.220 at 30 percent).

3.25.3.3 Effect of Asphalt. Asphalt grade was determined not to influence creep coefficient b of asphalt-rubber mixtures tested.

3.26 Sliding Plate First Cycle Creep Coefficient n

3.26.1 Calculated and analyzed creep coefficient n data is tabulated in Appendix Z in Table Z-1.

3.26.1.1 Average coefficient of variation for Atlos rubber at all concentrations and both asphalts was 14.3 percent compared to 12.0 percent for the U.S. Rubber Reclaiming rubber.

3.26.1.2 Average coefficients of variation for each rubber type at all concentrations and for both asphalts are:

- TP044 - 13.9%
- TP027 - 10.2%
- 50/50 TP044/TP027 - 25.5%
- GT274 - 12.1%
- USRF - 12.6%
- 50/50 GT274/USRF - 7.5%

3.26.1.3 Average coefficients of variation for each rubber concentration for all rubber types and both asphalts are:

- 15% - 17.2%
- 20% - 13.9%
- 25% - 14.8%
- 30% - 6.7%

3.26.1.4 Average coefficient of variation for all mixtures containing AR4000 asphalt was 14.9 percent and for the AR1000 11.2 percent.

3.26.1.5 Variability of calculated creep coefficient n data as indicated by coefficient of variation does not appear to be influenced by rubber type or asphalt grade, but tends to decrease as rubber concentration increases.

3.26.2 The ANOVA summary for creep coefficient n data is tabulated in Table Z-2.

3.26.2.1 Concentration and the rubber-asphalt interaction are significant effects at the 0.01 level. All other main effects and interactions are not significant.

3.26.3 Analysis indicates that rubber concentration and the rubber-asphalt interaction influence creep coefficient n data.

3.26.3.1 Effect of Rubber Concentration. Overall average creep coefficient n for asphalt-rubber mixtures tested is 0.725. The highest creep coefficient n value is obtained at 20 percent rubber (0.796 overall average) and lowest at 30 percent rubber (0.674 overall average).

3.27 Sliding Plate First Cycle Recovery Coefficient S_m

3.27.1 Calculated recovery coefficient S_m data are tabulated in Appendix AA in Table AA-1.

3.27.1.1 Average coefficient of variation for Atlos rubber at all concentrations and both asphalts was 20.4 percent compared to 26.9 percent for the U.S. Rubber Reclaiming rubber.

3.27.1.2 Average coefficients of variation for each rubber type at all concentrations and for both asphalts are:

- TP044 - 29.7%
- TP027 - 15.1%
- 50/50 TP044/TP027 - 18.9%
- GT274 - 21.9%
- USRF - 26.2%
- 50/50 GT274/USRF - 34.9%

3.27.1.3 Average coefficients of variation for each rubber concentration for all rubber types and both asphalts are:

- 15% - 39.7%
- 20% - 30.1%
- 25% - 10.9%
- 30% - 13.7%

3.27.1.4 Average coefficient of variation for all mixtures containing AR4000 asphalt was 28.5 percent and for the AR1000 20.6 percent.

3.27.1.5 Variability of calculated recovery coefficient S_m data as indicated by coefficient of variation does not appear to be affected by rubber type, tends to decrease as rubber concentration increases, and may be less for AR1000 than AR4000 asphalt.

3.27.2 Numerous attempts were made to transform recovery coefficient S_m data in order to comply with variance homogeneity requirements, but all were unsuccessful. Therefore, ANOVA could not be performed with the data. The following discussion is based only on average data from Table AA-1. Data were not plotted.

3.27.2.1 Average recovery coefficient S_m for Atlos rubber mixtures is 0.079 compared to U.S. Rubber Reclaiming mixtures, 0.130.

Within Atlos rubber mixtures average recovery coefficient S_m does not vary widely (0.081 for TPO44, 0.80 for TPO27, and 0.075 for the 50/50 TPO44/TPO27 mixture). Recovery coefficients S_m of U.S. Rubber Reclaiming mixtures vary to a greater extent (0.109 for GT274, 0.134 for USRF, and 0.148 for the 50/50 GT274/TPO27 mixtures).

3.27.2.2 For Atlos rubber mixtures, average recovery coefficient S_m does not vary with rubber concentration as much as with U.S. Rubber Reclaiming mixtures.

For U.S. Rubber Reclaiming mixtures as rubber concentration increases, average recovery coefficient S_m increases (0.097 at 15 percent rubber compared to 0.181 at 30 percent rubber).

3.27.2.3 For all rubber types and concentrations, asphalt-rubber mixtures containing AR4000 asphalt have lower average recovery coefficients S_m than mixtures containing AR1000 asphalt (0.078 overall average for AR4000 compared to 0.131 for AR1000).

3.28 Sliding Plate First Cycle Recovery Coefficient b

3.28.1 Calculated and analyzed recovery coefficient b data are tabulated in Appendix BB in Table BB-1.

3.28.1.1 Average coefficient of variation for Atlos rubber at all concentrations and both asphalts was 22.7 percent compared to 24.1 percent for the U.S. Rubber Reclaiming rubber.

3.28.1.2 Average coefficients of variation for each rubber type at all concentrations and for both asphalts are:

- TP044 - 22.0%
- TP027 - 26.2%
- 50/50 TP044/TP027 - 18.2%
- GT274 - 18.3%
- USRF - 30.0%
- 50/50 GT274/USRF - 25.4%

3.28.1.3 Average coefficients of variation for each rubber concentration for all rubber types and both asphalts are:

- 15% - 39.0%
- 20% - 20.3%
- 25% - 17.0%
- 30% - 17.3%

3.28.1.4 Average coefficient of variation for all mixtures containing AR4000 asphalt was 19.8 percent and for the AR1000 27.6 percent.

3.28.1.5 Variability of calculated recovery coefficient b data as indicated by coefficient of variation does not appear to be affected by rubber type, decreases as rubber concentration increases, and is less for AR4000 mixtures than AR1000 mixtures.

3.28.2 The ANOVA summary for recovery coefficient b is tabulated in Table BB-2.

3.28.2.1 Rubber type, concentration, and asphalt are significant effects at the 0.01 level. The rubber-concentration-asphalt interaction is significant at the 0.05 level but not at 0.01. All two-way interactions are not significant at the 0.05 level.

3.28.3 Analyses indicate that rubber type, rubber concentration, asphalt, and one interaction influence recovery coefficient b data.

3.28.3.1 Effect of Rubber Type. Asphalt-rubber mixtures containing the 50/50 TPO44/TPO27 mixture had the highest average recovery coefficient b (0.183 overall average) while the GT274 mixtures had the lowest (0.125 overall average).

Mixtures containing Atlos rubber had higher average recovery coefficient b (0.166 overall average) than U.S. Rubber Reclaiming mixtures (0.130 overall average).

Within both Atlos and U.S. Rubber Reclaiming rubber mixtures recovery coefficient b data do not vary greatly with rubber size (Atlos - 0.166 overall average for TPO44, 0.148 for TPO27, and 0.183 for the 50/50 TPO44/TPO27 mixture; U.S. Rubber Reclaiming - 0.125 for GT274, 0.130 for USRF, 0.136 for the 50/50 GT274/USRF mixture).

3.28.3.2 Effect of Rubber Concentration. For asphalt-rubber mixtures containing Atlos rubber, as rubber concentration increases, average recovery coefficient b tends to increase (0.150 average at 15 percent rubber as compared to 0.178 at 30 percent).

Average recovery coefficient b of mixtures containing U.S. Rubber Reclaiming rubber tends to increase to a greater extent as rubber concentration increases (0.088 average at 15 percent rubber compared to 0.164 at 30 percent) than with Atlos rubber.

3.28.3.3 Effect of Asphalt. Average recovery coefficient b for mixtures containing AR4000 asphalt was lower than for mixtures containing AR1000 (0.135 overall average for AR4000 compared to 0.161 for AR1000).

3.29 Sliding Plate First Cycle Recovery Coefficient n

3.29.1 Calculated creep coefficient n data are tabulated in Appendix CC in Table CC-1.

3.29.1.1 Average coefficient of variation for Atlos rubber at all concentrations and both asphalts was 15.6 percent compared to 19.5 percent for the U.S. Rubber Reclaiming rubber.

3.29.1.2 Average coefficients of variation for each rubber type at all concentrations and for both asphalts are:

- TP044 - 13.3%
- TP027 - 21.5%
- 50/50 TP044/TP027 - 12.5%
- GT274 - 24.8%
- USRF - 13.5%
- 50/50 GT274/USRF - 20.0%

3.29.1.3 Average coefficients of variation for each rubber concentration for all rubber types and both asphalts are:

- 15% - 32.8%
- 20% - 13.2%
- 25% - 11.9%
- 30% - 12.3%

3.29.1.4 Average coefficient of variation for all mixtures containing AR4000 asphalt was 20.8 percent, and for the AR1000, 15.1 percent.

3.29.1.5 Variability of calculated recovery coefficient n data as indicated by coefficient of variation does not appear to be greatly influenced by rubber type, or asphalt grade, but appears to decrease as rubber concentration increases.

3.29.2 Numerous attempts were made to transform recovery coefficient n data in order to comply with variance homogeneity requirements, but all were unsuccessful. Therefore, ANOVA could not be performed on the data. The following discussion is based only on average data from Table CC-1. Data were not plotted.

3.29.2.1 Average recovery coefficient n for Atlos rubber mixtures is 0.767 compared to 0.740 for U.S. Rubber Reclaiming mixtures. Within both Atlos and U.S. Rubber Reclaiming rubber types, recovery coefficient n does not appear to vary with rubber size (Atlos - 0.783 average for TPO44, 0.779 for TPO27, and 0.738 for the 50/50 TPO44/TPO27 mixtures; U.S. Rubber Reclaiming - 0.767 for GT274, 0.783 for USRF, and 0.672 for the 50/50 GT274/USRF mixture).

3.29.2.2 Average recovery coefficient n data do not appear to vary with rubber concentration for either Atlos or U.S. Rubber Reclaiming mixtures (0.735 overall average at 15 percent rubber compared to 0.753 at 30 percent).

3.29.2.3 Average recovery coefficient n data do not appear to vary with asphalt grade (0.768 overall average for AR4000 compared to 0.739 for AR1000).

3.30 Arizona Torque Fork Viscosity During Mixing at 375F (191C)

3.30.1 Measured mixing viscosity data at 15 minutes and 1 hour by the Torque Fork are tabulated in Appendix DD in Table DD-1. Since mixtures were not replicated, statistical analysis could not be performed.

3.30.2 Measured mixing viscosity data are plotted in Appendix DD in Figures DD1 through DD12.

3.30.3 From Figures DD1 through DD6, it can be seen that as rubber concentration increases for all rubber types and both asphalts, viscosity as measured by the Torque-Fork at both 15 minutes and 1 hour of mixing increases. These viscosity increases are the result of increased internal friction in the mixture due to increased particle-to-particle contact as rubber concentration increases. Average viscosities at 15 minutes are 13.2 poise at 15 percent rubber compared to 87.3 poise at 30 percent rubber. Average one hour viscosities are 15.3 poise at 15 percent rubber compared to 154.3 poise at 30 percent.

3.30.4 Examination of Figures DD7 through DD12 shows that for all mixtures investigated viscosities at 1 hour of mixing were higher than at 15 minutes indicating that mixtures become thicker during extended periods of mixing at 375F. Greater increases in viscosity between 15 minutes and 1 hour of mixing are noted at higher rubber concentrations than low. Asphalt-rubber mixtures containing U. S. Rubber reclaiming rubbers experienced greater viscosity increases at 25 and 30 percent rubber than mixtures containing Atlos rubber.

3.31 Haake Viscosity During Mixing at 375F (191C)

3.31.1 Measured mixing viscosity data at 15 minutes and 1 hour by the Haake viscometer are tabulated in Appendix EE in Table EE-1. Since readings were not replicated, statistical analyses could not be performed.

3.31.2 Measured mixing viscosity data are plotted in Appendix EE in Figures EE1 through EE12.

3.31.3 From Figures EE1 through EE6, it can be seen that as rubber concentration increases for all rubber types and both asphalts, viscosity as measured by the Haake viscometer at both 15 minutes and 1 hour of mixing increases. Increases in viscosity is due to increased interval friction as rubber concentration increases. Average Haake viscosity at 15 minutes mixing are 9.8 poise for 15 percent rubber compared to 260 poise for 30 percent rubber. After one hour of mixing, average Haake viscosity at 15 percent rubber is 18.9 poise compared to 294 poise at one hour.

3.31.4 Examination of Figures EE7 through EE12 shows, that with several exceptions, Haake viscosities increase between 15 minutes and one hour of mixing. Additionally, it is noted that the highest viscosities during mixing are obtained with U.S. Rubber Reclaiming rubbers than with Atlos rubbers.

3.31.5 Figure 8 is a plot of mixture viscosity as measured by the Torque-Fork versus viscosity as measured by the Haake viscometer. Data at both 15 minutes and 1 hour is plotted. From Figure 8, it is noted that the Haake viscometer measures a higher viscosity than the Torque-Fork. Linear regression of the data yields the following relationship:

$$H = -6.53 + 2.62\ (TF)$$

in which

H = Haake viscosity at 375F, Poise

TF = Torque-Fork viscosity at 375F and 500 RPM, Poise

The r^2 value for this fit is 0.72. The fit, as indicated by the F test, is highly significant at the 0.01 level.

3.31.6 Differences which exist in viscosities as measured by the Torque-Fork and Haake may be due to the different rotational speeds of the two devices (500 RPM for the Torque-Fork and 62.5 RPM for the Haake.

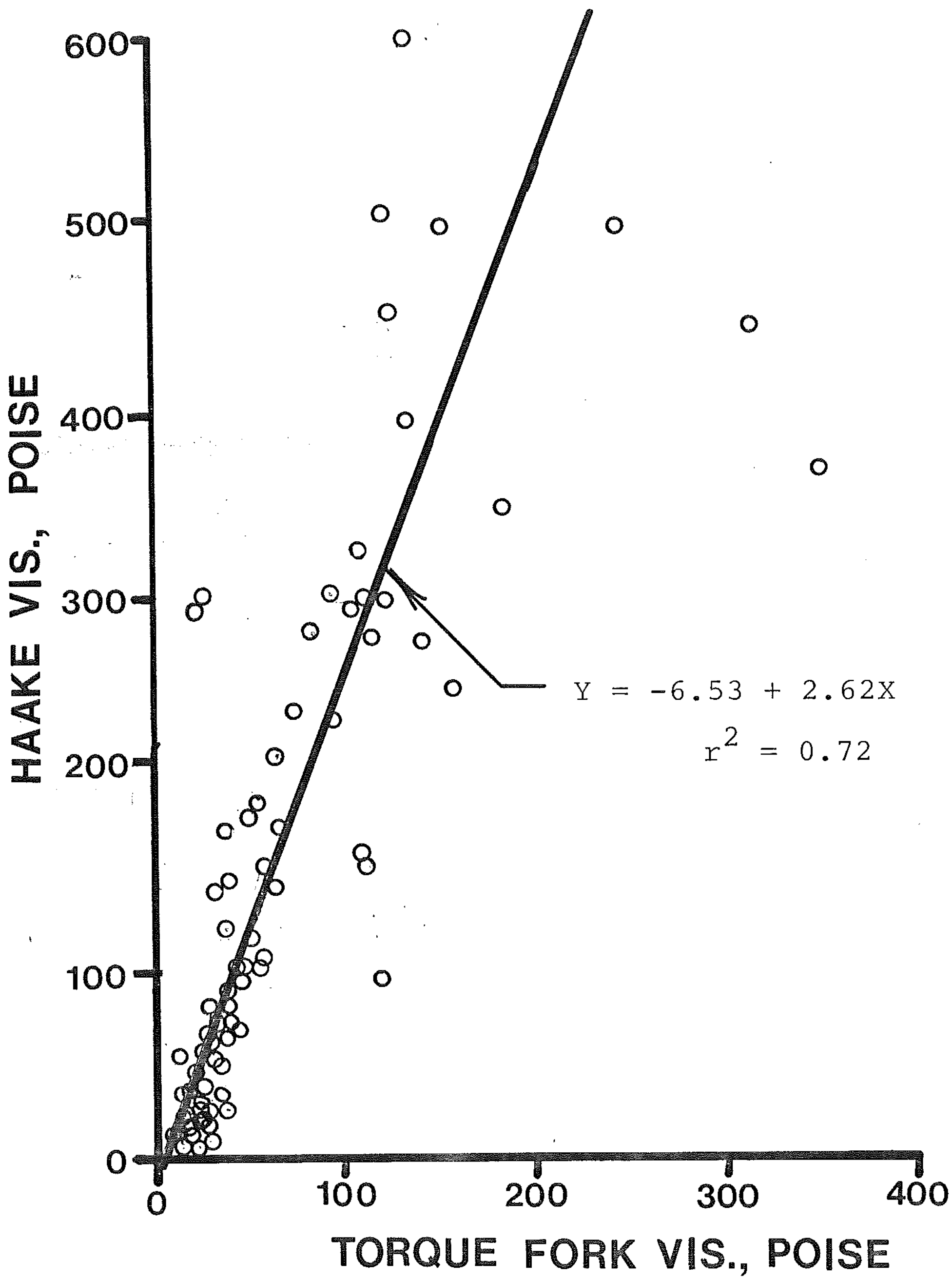

Figure 8 Torque-Fork Versus Haake Viscosity Relationship

4.0 CONCLUSIONS

4.1 A summary of three-way ANOVA results is tabulated in Table 1. This table indicates independent variables and interactions which were found to significantly affect test parameters studied during this investigation. From Table 1 it is easily seen that constituent materials in an asphalt-rubber mixture, rubber type and concentration, and asphalt, significantly influence many of the test parameters considered in this study.

4.2 The following specific conclusions are based on test results, statistical analyses, and interpretation performed during this study.

4.2.1 Results indicate that the absolute viscosity at 140F (60C) of asphalt-rubber mixtures is different for mixtures containing different rubber types and particle sizes, different rubber concentrations, and different asphalt grades. Variability of test results is high (coefficients of variation of 20 percent were common during testing) even with the large capillary tube bore sizes utilized. Data generated tend to indicate that increasing rubber particle size and concentration may increase testing variability.

Test results varied from a low of 7,636 poises to a high of 691,256 poises for different formulations.

4.2.2 Shear susceptibility and apparent viscosity of asphalt-rubber mixtures as measured by the Schweyer Rheometer at 39.2F (4C) were found to be different for different rubber types and sizes and concentration. Asphalt grade did not influence shear susceptibility, but did influence apparent viscosity.

Testing variability for the parameters considered was high (many coefficients of variation in excess of 25 percent for shear susceptibility and 50 percent for apparent viscosity). Data indicate that rubber particle size may influence testing variability. Test results for larger rubbers (TP044) are more variable than with smaller rubbers (USRF). These differences may be due to increased flow interference as particle size increases.

Table 1 Summary of Three-Way ANOVA Results at the 0.05 Level of Significance

TEST PARAMETER / EFFECT	R	Q	A	RQ	RA	QA	RQA
ABSOLUTE VISCOSITY (140F)	Y*	Y	Y	Y	Y	–	Y
SCHWEYER RHEOMETER (39.2F)							
Constant(C), G-tube	Y	Y	–	–	–	–	–
Constant(C), F-tube	Y	Y	–	Y	Y	–	Y
App. Viscosity, G-tube	Y	–	Y	–	–	–	–
App. Viscosity, F-tube	Y	Y	Y	Y	Y	–	–
FORCE DUCTILITY (39.2F)							
Load at Failure	Y	Y	Y	Y	Y	Y	Y
Elongation at Failure	Y	Y	Y	Y	–	Y	Y
Eng. Stress at Failure	Y	Y	Y	Y	Y	Y	–
Eng. Strain at Failure	Y	Y	Y	Y	–	Y	Y
True Stress at Failure	Y	Y	Y	Y	–	Y	–
True Strain at Failure	Y	Y	Y	Y	–	Y	Y
Eng. Creep Compliance	Y	Y	Y	Y	Y	Y	Y
True Creep Compliance	Y	Y	Y	Y	Y	Y	Y
Max.True Creep Compliance	Y	Y	Y	Y	Y	Y	Y
Time to Max.T.Creep Compl.	Y	Y	Y	Y	–	Y	–
SLIDING PLATE MICRO-VISCOMETER (32F)							
App. Viscosity	Y	Y	Y	Y	Y	Y	Y
1st Cycle 30 min. Creep	Y	Y	Y	Y	–	Y	–
1st Cycle 30 min.Recovery	Y	Y	Y	Y	–	–	–
2nd Cycle 30 min. Creep	Y	Y	Y	Y	Y	Y	Y
2nd Cycle 30 min.Recovery	Y	Y	Y	Y	–	–	Y
2nd Cycle 20 hr. Recovery	Y	Y	Y	Y	–	–	–
2nd Cyc.20 hr.30 min.Recov.	Y	Y	Y	Y	–	–	–
1st Cycle % Rebound	Y	Y	Y	Y	Y	Y	–
1st Cylcle b	Y	Y	–	Y	Y	–	–
1st Cycle n	–	Y	–	–	Y	–	–
2nd Cycle b	Y	Y	Y	–	–	–	Y

*NOTE: Y = Significant at the 0.05 level
– = Not significant at the 0.05 level

Asphalt-rubber mixtures tested tended to be more pseudoplastic in nature than dilatent as indicated by the Schweyer Rheometer.

Viscosity of mixtures tested varied from a low of 17.5 x 10^6 Pa-s to a high of 55,210 x 10^6 Pa-s for different formulations.

4.2.3 Stress, strain, and creep compliance characteristics of asphalt-rubber mixtures, as measured by the force-ductility test at 39.2F (4C) were found to be different for mixtures containing different rubber types and particle sizes, different rubber concentrations, and different asphalt grades. Testing variability for many of the parameters considered was rather low, coefficients of variation were generally less than 10 percent, when compared to other test types considered. It is suggested that lower testing variability is related to the unconfined tensile nature of the test which would not result in rubber particle interference with testing apparatus as with absolute viscosity, Schweyer Rheometer, or sliding plate microviscometer testing.

True stress at failure varied from a low of 296 psi to a high of 1279 psi while true strain at failure varied from 1.41 mm/mm to 2.46 mm/mm for different formulations.

4.2.4 Apparent viscosity, creep, recovery, and rebound charcteristics of asphalt-rubber mixtures, as measured by the sliding plate microviscometer, were found to be different for different rubber types and particle sizes, different rubber concentrations, and different asphalts. Interactions between mixture components were identified by several of the measurements. Testing variability was rather low (less than 15 percent coefficients of variation) for several of the parameters - second cycle creep and recovery, and first cycle percent rebound and creep, but high (coefficients of variation between 15 and 50 percent) for others.

4.2.5 Viscosity during mixing at 375F (191C) as measured to Arizona Torque-Fork or Haake Viscometer of asphalt-rubber varies depending on rubber types, rubber concentration, and asphalt type. The reaction between rubber and asphalt can be monitored during mixing using either device by monitoring mixture viscosity changes. A significant relationship between Haake and Torque-Fork viscosity measurements was found to exist.

4.3 The following general conclusions were reached based on results of this study.

4.3.1 Physical properties of asphalt-rubber mixtures from 32F (0C) to 375F (191C) can vary widely and depend on the type of rubber utilized, rubber concentration, and asphalt grade.

4.3.2 The force-ductility test is the most sensitive to changes in mixture components and is the least variable test investigated in this study.

References

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